

## Damage to residential buildings due to flooding of New Orleans after hurricane Katrina

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**Abstract** This article analyzes the direct damage to residential buildings caused by the flooding of New Orleans after hurricane Katrina in the year 2005. A public dataset has been analyzed that contains information on the economic damage levels for approximately 95,000 residential buildings in the flooded area. The relationship between the flood characteristics and economic damage to residential buildings has been investigated. Results of hydrodynamic flood simulations have been used that give insight in water depths and flow velocities in the study area. In general, differences between the three polders in the observed distributions of damage estimates are related to differences in flood conditions. The highest damage percentages and structural damage mainly occurred in areas where higher flow velocities occurred, especially near the breaches in the Lower 9th Ward neighborhood. Further statistical analysis indicated that there is not any strong one-to-one relationship between the damage percentage and the water depth or the depth–velocity product. This suggests that there is considerable uncertainty associated with stage–damage functions, especially when they are applied to individual structures or smaller clusters of buildings. Based on the data, a more general approach has been proposed that could be used to distinguish different damage zones based on water depth and flow velocity for an area that is affected by flooding due to breaching of flood defenses. Further validation of existing damage models with the dataset and further inclusion of information on building type in the analysis of damage levels is recommended.

**Keywords** Flooding · Damage · Residential buildings · Damage function · Depth–velocity product · Hurricane Katrina · New Orleans

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## 1 Introduction

### 1.1 Background and objective

The catastrophic flooding in the United States after hurricane Katrina in late August 2005 caused enormous economic damage and human suffering in the states of Louisiana and Mississippi. It is estimated that hurricane Katrina left more than 204,000 homes in Louisiana uninhabitable, damaged, or destroyed (FEMA 2006). Especially, the city of New Orleans was severely affected. An estimate of direct property and infrastructure damage due to flooding was published in the “consequences” report of the Interagency Performance Evaluation Team (IPET 2007a). The report conveyed that flood damage to residential property in New Orleans is estimated at US\$16 billion and damage to public structures, infrastructure, and utilities (like roads, railroads, water defenses, electricity network, drainage etc.) at US\$7 billion.

Several publications discuss other types of consequences due to hurricane Katrina, such as the loss of life (Jonkman et al. 2009), the physical and mental health impacts (Bourque et al. 2006; Sullivent et al. 2006), and the pollution from industrial and household chemicals that mixed with floodwaters (Pardue et al. 2006). Several sources gave insights in the economic damage relatively shortly after the hurricane. The Department of Homeland Security (DHS) (2006) compiled detailed tables to assess the full extent of housing damage due to Hurricanes Katrina, Rita, and Wilma. Brinkmann and Ragas (2006) investigated the economic viability of the repair or replacement of the many damaged residential properties in New Orleans. Hallegatte (2008) presented a study of the indirect damages that occurred outside the flooded area in the Louisiana economy. These publications were mainly based on data that were available in the year after the disaster and the application of existing models for damage prediction.

This article focuses on the direct damage to residential buildings caused by the flooding of New Orleans after hurricane Katrina. The objective of this article is to improve the insight in the relationship between the flood characteristics and the direct damage to residential buildings. This is done based on a dataset that was collected in the aftermath of the flooding. The dataset contains information on the damage for approximately 95,000 residential buildings and this data were mainly collected by means of surveys and inspections in the field. The size of the damage dataset is exceptionally large, and the analysis will contribute to a stronger empirical basis of flood damage analyses. The flood conditions that developed due to hurricane Katrina are a combination of multiple sources of flooding (e.g. rainfall, storm surge, levee breach etc.) and resulted in particularly severe loadings on structures. Besides flood depth, the effects other flood characteristics are examined, in particular the effects of flow velocity.

The outline of this article is as follows. The remainder of this section describes existing concepts for damage estimation. Section 2 gives the background history of the flooding of New Orleans due to hurricane Katrina and presents a summary of the results of hydrodynamic simulations of the flooding conditions. Section 3 describes the damage dataset and its derivation. The relationship between flood depth and economic damage is examined for the flood affected area of New Orleans in Sect. 4. Section 5 analyzes the relationship between the combination of flood depth and flow velocity and the economic damage for the severely damaged neighborhood Lower 9th Ward. A discussion of the findings and their implications is included in Sect. 6. Final conclusions and recommendations are described in Sect. 7.

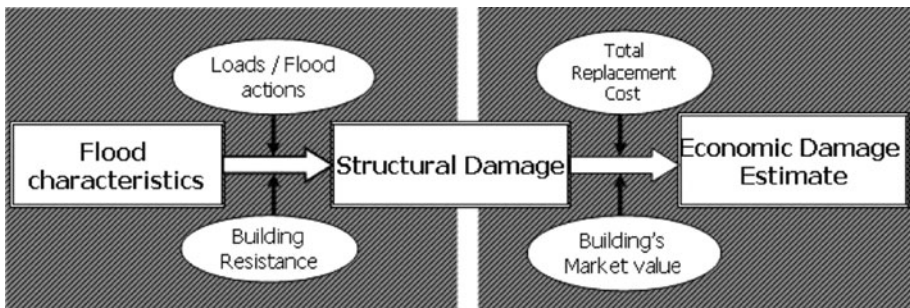
### 1.2 General approach for damage estimation

In general, the estimation of direct economic flood damage involves two related steps, see Fig. 1. The first one is the analysis of structural damage caused by the flood effects. This will be determined by the flood actions (or loads) and the building resistance (Kelman and Spence 2004). The degree of structural damage depends on the intensity and magnitude of the flood actions, i.e. hydrostatic and hydrodynamic forces, and on the building’s resistance to flooding. The next step is the economic valuation of the physical damages. To convert the structural damage to economic estimates, insight in the building’s pre-disaster market value and the replacement cost is required. Apart from damage to the structure, the damage estimation in monetary terms will also involve an assessment of the damage to the inventory of the structure.

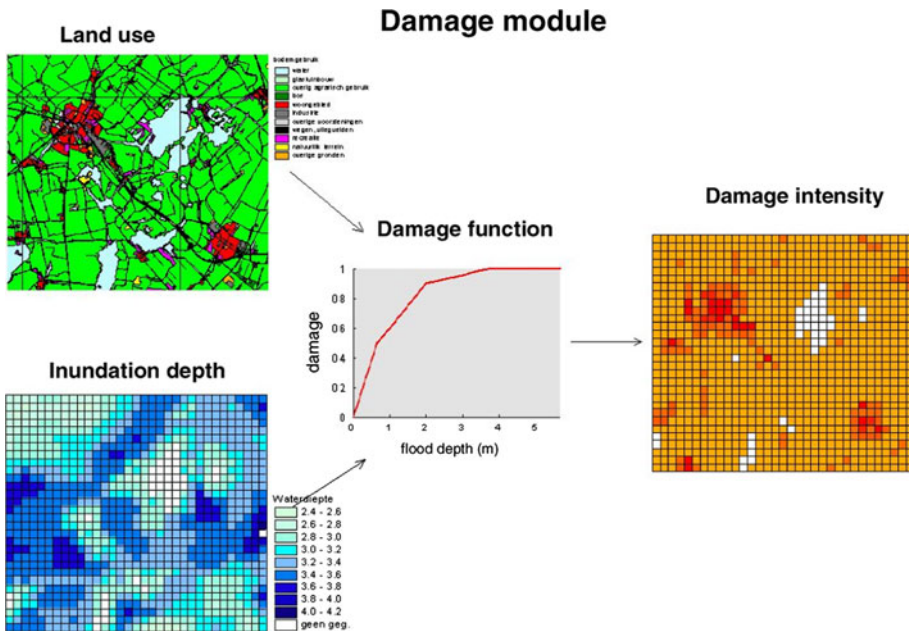
In practice, the assessment of direct (economic) damage to buildings is often directly related to the flood characteristics without a direct analysis of the physical mechanisms that cause the damage. For instance, damage may result from energy transfer, forces, or pressures leading to effects on buildings including wall failure, doors being forced open, glass breaking, roofs collapsing, or foundations being undermined. However, there is limited knowledge about the physical causes of flood damage beyond the description of flood characteristics (Kelman and Spence 2004).

The general procedure for the estimation of direct physical damages is visualized in Fig. 2. The procedure comprises three main elements: (1) determination of flood characteristics; (2) assembling information on land use data and maximum damage amounts; (3) application of stage-damage functions that relate the extent of economic damage to the flood characteristics.

Stage-damage functions are often derived based on empirical data for historical floods, and they express the damage as a percentage or fraction of the total value of a flood-affected building. Most stage-damage functions include water depth as the main determinant of direct damage (Merz et al. 2004; Smith 1994; USACE 1996; Penning-Rowsell and Fordham 1992; Jonkman et al. 2008). However, recent studies have shown that depth-damage functions may have a large uncertainty since water depth and building use only explain a part of the data variance (Merz et al. 2004; Egorova et al. 2008). Flood damage is influenced by many more factors among which are flow velocity, flood duration, contamination, sediment concentration, lead time and information content of flood warning, building characteristics (elevation, structure, etc.), and the quality of external response in a flood situation (Smith 1994; USACE 1996; Kelman and Spence 2004; Merz et al. 2004).



**Fig. 1** Scheme of flood damage analysis



**Fig. 2** Schematization of the estimation of direct damage due to flooding (source Rijkswaterstaat 2005)

Except for conceptual models, the earlier mentioned factors are, though, scarcely included in flood loss models.

## 2 The flooding of New Orleans and simulation of the flood characteristics

### 2.1 Background: the flooding of New Orleans due to hurricane Katrina

The metropolitan area of Greater New Orleans is situated in the Mississippi Alluvial Plain between the Mississippi River in the south and Lake Pontchartrain in the north. The city and its surrounding suburbs are largely below sea level and entirely surrounded by levees. As a consequence of its geographical situation, the area is vulnerable to flooding from hurricanes, high discharges of the Mississippi river, and heavy rains. The metropolitan area that was affected by the flooding consists of three bowls or so-called polders: the Central polder, New Orleans East polder, and St. Bernard polder (Fig. 3).

On Monday, the 29th of August 2005, hurricane Katrina made landfall at the shores of Louisiana. In the eastern region of the city, including New Orleans East polder and the St. Bernard polder, the flooding was caused primarily by levee overtopping and consequent levee and floodwall failures. In the central part of the city (Central polder), most of the flooding was caused by failures of floodwalls in the three drainage outfall canals leading to Lake Pontchartrain.

As a result of the levee/floodwall breaches, widespread flood damage to residential neighborhoods occurred throughout the New Orleans metropolitan area. The depth of flooding within the New Orleans area varied greatly, as did damage to structures. In all,



**Fig. 3** The three bowls that comprise Greater New Orleans (Kok et al. 2007)

nearly 80% of the housing stock in the city was destroyed or severely damaged and over 1,000 lives were lost in New Orleans and Southeast Louisiana (FEMA 2006).

## 2.2 Summary of simulations of flood characteristics

In this study, results of hydrodynamic flood simulations have been used to analyze the relationship between flood characteristics and damage to buildings. These are the results of a flood simulation project performed by TU Delft and Svasek Hydraulics (Kok et al. 2007). Flood simulations were generated for the three polders i.e. Central polder, East polder, and St Bernard polder, utilizing the best available input data and the software package SOBEK 1D2D (Delft Hydraulics 2003). The mathematical model consists of a two-dimensional flow model that is based on the Saint–Venant equations. Flooding was simulated with a combination of 1D (one-dimensional) and 2D (two-dimensional) elements; canals and boundaries were modeled as 1D elements and the overland flooding itself was modeled as a 2D process. The 2D area in the model consisted of a grid with computational cells of 50 m. Sobek-1D2D calculated the water levels and velocities in every grid cell. The following sources of flooding were taken into account for the simulation:

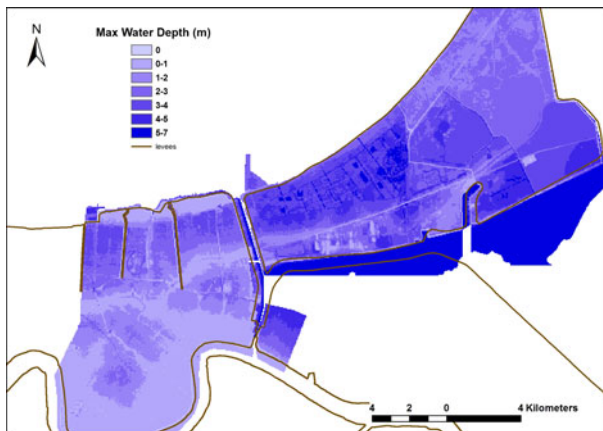
- Rainfall and effects of pumping stations
- Overtopping of the levees and flood control structures
- Breaches of levees and/or floodwalls

The hydrodynamic model generated output information about the development of the flood flow over time and provided insight in flood characteristics, such as water depth, flow velocity, and the rise rate of the water. All the characteristics were available at all sites, and the maximum values of the flood characteristics were used for the economic damage analysis in this paper. The water depth is defined as the difference between the flood level and the land elevation. The rise rate was determined over the first 1.5 m of water depth, and it is expressed with the unit [m/h]. Also, the combination of water depth ( $d$ –[m]) and flow velocity ( $v$ –[m/s]) was considered in the analysis of building damage (see Sect. 5.1 for further details). This so-called depth–velocity product is denoted in this article as  $dv$  with unit [m<sup>2</sup>/s].

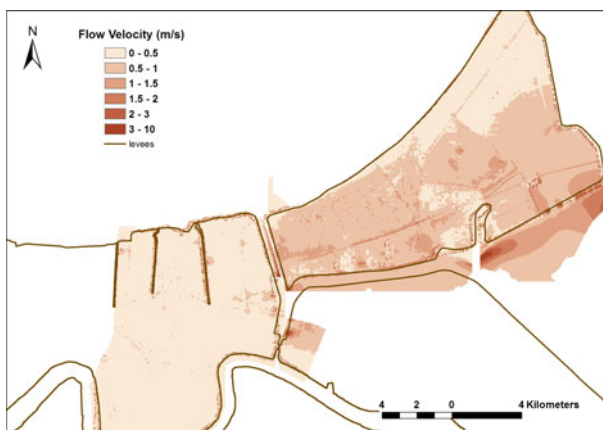
The results of flood simulations were compared with data/observations presented in the report of the Interagency Performance Evaluation Task Force (IPET (Interagency Performance Evaluation Task Force) 2007b) in the format of eye witness accounts, stopped clock times, and time/date stamped digital photographs. The computed flood hydrographs were similar to the data presented by IPET, and for the purpose of this study, the model results were considered applicable. Kok et al. (2007) discuss further details regarding the simulation process, the assumptions and the validation of the simulations.

Figures 4, 5, 6, and 7 show the simulated maximum values of water depth, velocity, the depth–velocity product, and rise rate over the first 1.5 m of water depth for the Central polder, New Orleans East polder, and the Lower 9th Ward neighborhood of the St. Bernard polder.

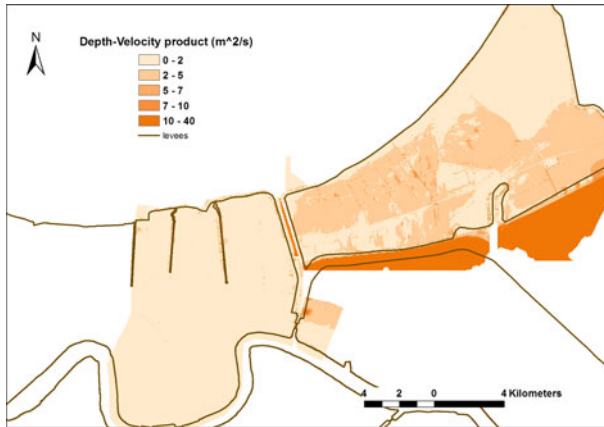
We note that in the figures shown the simulation resulted in high values of almost all flood characteristics south of the southern levee of the New Orleans East polder. This effect



**Fig. 4** Maximum water depth values as resulted from the simulation



**Fig. 5** Maximum flow velocity values as resulted from the simulation



**Fig. 6** Product of maximum values of depth and velocity as resulted from the simulation



**Fig. 7** Maximum rise rate values over the first 1.5 m as resulted from the simulation

occurs due to the assumption that the levees are modeled as 1D elements with certain boundary conditions for flow velocity and water depth. In this area, no residential buildings were present, and thus the values for this particular area were not considered in the damage analysis.

The simulations show that the most severe flooding conditions occurred in the Lower 9th Ward neighborhood of the St. Bernard polder. Depths in Lower 9th reached 4–5 m in the deepest parts and high flow velocities (3–10 m/s) were found in the simulations near the two breaches of the levees. In the Central polder, the flow velocities were high (1–2 m/s) only very near the breaches, and the water depths were relatively large (>3 m) only in some locations, especially in the northern part of the polder. Finally, we observed that the New Orleans East polder suffered large water depths (>4 m) that covered gradually most of the area of the polder. However, maximum flow velocities in this area were lower than those in the Lower 9th Ward.

### 3 The damage dataset

#### 3.1 Introduction

A dataset with information on damage to residential buildings was created by the city of New Orleans in order to better serve the public and enhance the recovery process from the damage that the hurricane Katrina caused. This information was made available at the CNOGIS, the city of New Orleans GIS Data sharing portal (<http://gisweb.cityofno.com/cnogis/dataportal.aspx>, accessed in March 2008). The data from this source was compiled into an independent GIS dataset by using ArcView 9.1 and ArcView 9.2 geocoder with StreetMaps USA. The damage dataset contains information for approximately 95,000 residential buildings in Orleans parish. Information for other areas and parishes in Louisiana that were affected by Katrina was not included.

Since the focus of the damage analysis was on single-family residential buildings, the damage dataset includes the following information for every property: location (street address, census block id, neighborhood, zip code, planning district, xy coordinates) and the estimated damage percentage. In the original dataset, there is no available information on the building or structure type for individual properties.

#### 3.2 Overview of the dataset

In order to identify what the housing damage estimates represent and how the damage estimates were determined, the authors reviewed available published documentation made available by the city of New Orleans, as well as official reports from FEMA, the U.S. Department of Homeland and Security and the city's Department of Safety and Permits (FEMA 2006; IPET 2007a; Skinner 2006). According to the available sources, the percent damage estimates are defined as the percentage of pre-Katrina building's market value that is damaged, i.e. the ratio of the cost to repair/improve a building to the market value of the building before the disaster:

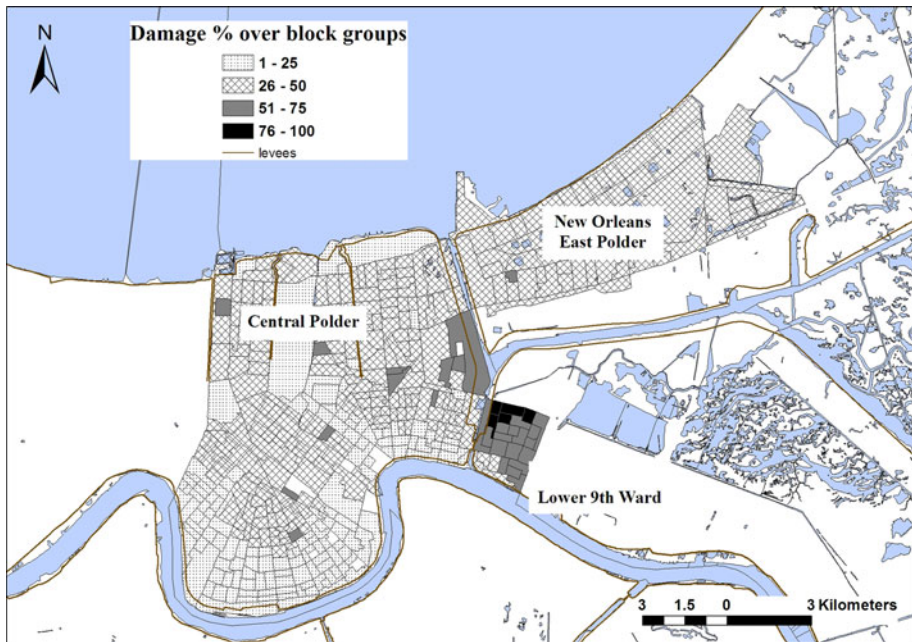
$$\text{Percentage damage value} = \frac{\text{Cost of repairs}}{\text{Market value of building}} \quad (1)$$

In the remainder of this article, the percent damage value is at some locations also indicated as damage fraction, with values between 0 and 1 (i.e. between 0 and 100%). The damage dataset covers Orleans parish and thereby most of the residential properties within Central polder and East polder. For the St. Bernard polder, it covers the neighborhood Lower 9th Ward. Figure 8 gives an overview of the three polders and the average housing damage value by block group. Block groups are spatial units used as standard aggregation levels for the 2000 US Census (GARM 1994). On average, block groups cover 0.07 km<sup>2</sup> and include 400 houses.

The estimates of damage percentage in the dataset are largely based on direct inspections and surveys of individual residential properties by FEMA contract inspectors to determine eligibility for FEMA housing assistance. For some of the properties impacted by hurricane Katrina, the contract inspectors did not have access to the interiors of the homes, so they conducted damage assessments based on the water lines on the homes' exterior (Skinner 2006). Moreover, remote sensing techniques were used, where site inspections did not take place (Friedland 2009).

To overcome the problem of not having access to the homes, the USACE developed standardized guidesheets from a FEMA software program—Residential Substantial Damage





**Fig. 8** Damage dataset averaged over block group of the three polders of New Orleans

Estimator (RSDE)—designed for inspecting damaged homes. The guidelines estimated damage in 16 housing categories, but they included only three ranges for water depth: 0–1 feet, 2–7 feet, and 8 feet and greater. Hence, the guidelines used flood depth ranges that may have been too broad to produce accurate ratings (FEMA 2003; Skinner 2006).

The threshold of 50% damage value defines the concept of substantial damage, i.e. the damage sustained by a building whereby the cost of restoring the building to its pre-damaged condition would equal or exceed 50% of the market value of the building before the event occurred. Given the method used for damage rating, it is expected that damage percentages lower than 50% mainly indicate damage to the contents of the building, whereas damage values higher than 50% indicate some level of structural damage.

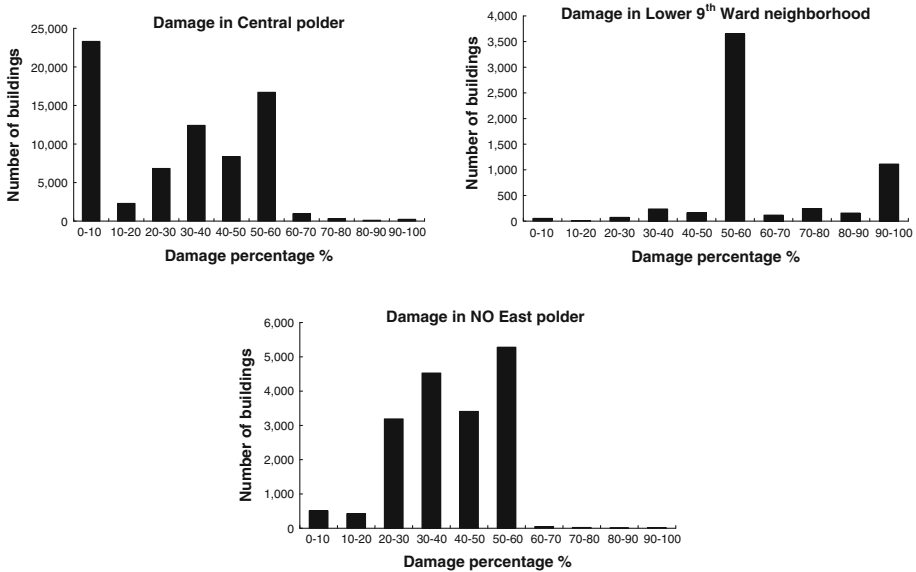
Hurricane Katrina was characterized by both severe flooding and wind effects. It is expected that flood conditions were far more destructive to buildings than wind effects in the city of New Orleans. The Mitigation Assessment Team (MAT) of FEMA found that in inland areas such as New Orleans wind speeds were lower than the design wind speeds. In these areas, some wind damage was common, but typically not as extensive or severe as in areas directly at the coast that were exposed to higher wind speeds (FEMA 2006; Friedland 2009). According to the same report, it was the storm surge and subsequent flooding which caused New Orleans’ catastrophic level of loss.

### 3.3 Statistical characteristics of the dataset

As of March 2nd 2006, city officials and FEMA contractors had completed almost 95,000 residential damage assessments. Table 1 and Fig. 9 summarize the properties of the dataset. The average damage rating is 43.3%, and approximately 27.6% of the units received a damage rating higher than 50% indicating some level of structural damage.

**Table 1** Descriptive statistics of the damage dataset by polder

Polder	Total dataset			Observations with damage levels >50%	
	No. of observations	Average damage (%)	Standard deviation of damage (%)	No. of observations	Percentage of total observations
Central polder	71,579	28.2	22.1	16,174	22.6
New Orleans East polder	17,451	39.0	12.9	4,876	27.9
Lower 9th Ward neighborhood	5,820	62.8	20.3	5,155	88.6
Total	94,850	43.3	20.8	26,205	27.6



**Fig. 9** Histograms of damage levels for each of the three polders in New Orleans. (Note: the vertical scales of the three pictures differ)

The earlier mentioned descriptive statistics are combined with observations on the flood conditions (see Sect. 2.2) and field observations by the authors and FEMA’s Mitigation Assessment Team (FEMA 2006) that performed numerous site visits to the area. This leads to the following general observations for the three polders.

*3.3.1 Lower 9th Ward neighborhood (St. Bernard polder)*

In this area, the average damage was the highest and a relatively large number of cases of large damage percentages occurred. Almost 90% of the damaged units were rated with a damage percentage higher than 50%. In this area, severe flooding conditions in terms of depth and velocity occurred due to two large breaches in the levees. Observations in Lower 9th Ward indicated widespread structural damage and destruction of residential buildings

from high-velocity floodwaters, winds waves, and high floodwaters that knocked buildings off their foundations, collapsed load-bearing walls, and caused other structural failures (FEMA 2006). Very high (95–100%) damage estimates mainly covered areas near the levee breaches (see also Sect. 5).

### 3.3.2 Central polder

In the Central polder, the highest values of flood depth were observed in the northern part of the polder, and the highest values of flow velocity were calculated only to the areas immediately behind of the breaches in the levees. The damage levels here varied largely, and the majority of damage values were lower than 50%. A relatively large number of houses with a low damage percentage (<10%) was found in this area. The relatively high standard deviation in the Central polder is expected to be related to the wide range of flooding conditions (see Figs. 4, 5) and the variation in the building types.

According to MAT (FEMA 2006), severe structural building damage or total failure in the Central Polder was restricted mostly to residential buildings immediately behind levees breaches, such as 17th Street Canal levee breach. Figure 10 shows an example of observed damage in that area. MAT reported that these buildings suffered failure of load-bearing walls and extensive scour around slab foundations from large hydrodynamic forces generated by the breach. For other parts of Central polder and also for the New Orleans East polder, widespread non-structural damage was considered as the typical damage pattern to residential buildings. MAT gave two primary reasons for this observation. First, the flooding in most of the areas of New Orleans was characterized by slow-moving floodwaters which greatly reduced or eliminated the damaging effects of hydrodynamic forces and flood borne debris impacts on buildings. Second, the crawl-spaces, garage bay doors, and other openings allowed hydrostatic pressures on walls and floors from floodwaters to equalize as floodwaters gradually rose and receded, which greatly reduced the net hydrostatic force on load-bearing walls, floors, and other structural elements.



**Fig. 10** Structural damage to a residential building located in the Central polder near the 17th Street Canal breach

### 3.3.3 New Orleans East polder

In the New Orleans East polder, there are also a relatively low number of cases of very large damage, whereas the flooding conditions involved high values of depth and rise rate. Similar to the Central polder, the dominant observed damage pattern here (FEMA 2006) was the widespread non-structural damage due to long duration flooding.

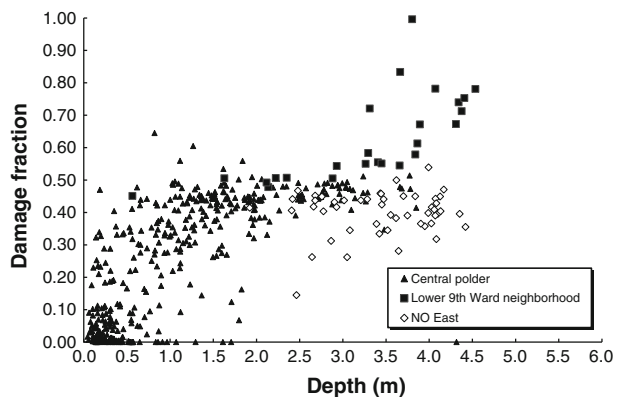
## 4 Analysis of the relationship between flood depth and economic damage

The relationship between the damage percentages and the different types of flood characteristics (depth, velocity, rise rate) has been analyzed by using the damage dataset and the output of the flood simulations. No clear relationship was found between the variable of rise rate and damage levels. For example, the same range of rise rate values was found for Central and St. Bernard polders (see also Fig. 7), but damage distributions were different for these areas. In this section, the results of an analysis based on water depth are presented. The effects of velocity in combination with depth are investigated in Sect. 5.

In the analysis, the flood depth has been spatially averaged over two types of standardized spatial aggregation levels: census blocks and block groups. According to 2000 US Census Bureau guidelines (GARM 1994), an ideal size for a block group is of 400 housing units, with a minimum of 250, and a maximum of 550 housing units. The guidelines further require that a block includes on average 15 housing units e.g. residential buildings. The minimum size of a block is 0.0028 km<sup>2</sup>.

Figure 11 shows the relationship between water depth and damage estimates, both averaged over block groups for all the three polders. There are two primary observations. First, there is a cluster of damage estimates in Central polder that is characterized by water depth values less than 0.5 m and damage values less than 10%. The occurrence of this cluster can likely be explained by two factors: (a) the typical type of residential building within the Central polder is a single-story building with some crawlspace under it, and these buildings are usually elevated a few decimeters above the ground (b) due to topography a large part of the Central polder had limited flood depths, especially along the edges of the flood zone (see also Fig. 4).

**Fig. 11** Relationship between depth and economic damage estimates over block groups



A second observation for the scatter plots of Fig. 11 is that a large part of the damage estimates was rated equal or below the 51% threshold value of substantial damage with the exception of the damage estimates in Lower 9th Ward area. Most of the damage estimates for the Lower 9th Ward are rated over 50% value, although the flood depth was similar to the depth in New Orleans East. This observation leads to the expectation that flood depth alone can not cause substantial damage unless high values of velocity are also involved.

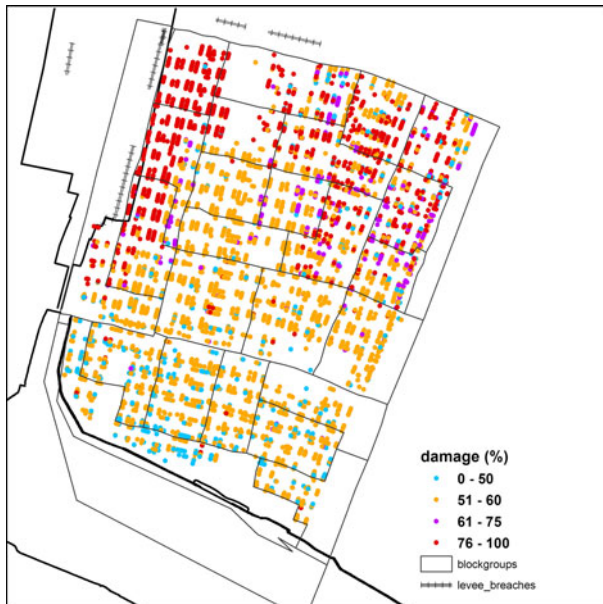
Several statistical distributions have been examined to provide a best fit function for the dataset, but, even for the best fitting functions (exponential and power fits), the squared correlation coefficient ( $R^2$ ) remained below a value of 0.5.

## 5 Analysis of the relationship between the depth–velocity product and economic damage

### 5.1 Background

The analyses in this section focuses on the Lower 9th Ward as the damage percentages were highest ones in New Orleans, and the area suffered severe damage due to extensive levee breaches. Flow velocities in the area were much higher than in other parts of New Orleans (see Fig. 5), and it is expected that this has contributed significantly to the high damage. Figure 12 illustrates the percent damage estimates by building for the Lower 9th Ward neighborhood.

Figure 13 shows a typical scene from near the southern breach in the levees along the Industrial Canal. The photo was taken from the levee, and the view is in the eastern direction. It shows that many buildings near the breach were totally destroyed, and this is consistent with the damage estimates in Fig. 12 that show values near a 100% for this zone.



**Fig. 12** Damage estimates for the buildings in the Lower 9th Ward neighborhood



**Fig. 13** Lower 9th Ward; view in the eastern direction from the levee at the location of the southern breach in the levees (February 20, 2006)

In this section, the effect of the combined load of water depth and flow velocity on flood damage is analyzed. The depth–velocity ( $dv$ ) product is considered by previous studies as a critical variable for damage to a collapse of buildings (Clausen 1989), and therefore it is also investigated in this article. According to Schwarz and Maiwald (2008), the relevance of flood velocity in combination with the flood level should be investigated for the establishment of damage prediction models, especially where a sudden increase of flow velocity is expected due to the hydraulic and topographical situation. In addition, the depth–velocity product is also an important factor for the analysis of instability of people in flood flows (Jonkman and Penning-Rowsell 2008).

First, the (physical) background of the depth–velocity product is discussed. For a block-shaped object, it relates to a flood action via the flow momentum's definition in the following way:

$$\begin{aligned} \text{Momentum} &= \text{mass} \times \text{velocity} = \text{density} \times \text{volume} \times \text{velocity} \Rightarrow \\ \text{Momentum} &= \text{density} \times \text{flooded horizontal area} \times (\text{depth} \times \text{velocity}) \end{aligned} \quad (2)$$

When density and flood horizontal area are considered constants, the depth–velocity ( $dv$ ) product remains as the variable that determines the load. In the presented analysis, the maximum values of water depth ( $d_{\max}$ ) and flow velocity ( $v_{\max}$ ) from the flood simulations have been combined to determine the  $dv$  product. It is noted that this is a somewhat conservative approach, since the maximum values of depth and maximum values of velocity do not need to have occurred simultaneously, i.e.  $d_{\max} v_{\max} > (dv)_{\max}$ .

## 5.2 Application of existing damage criteria

In this section, existing criteria for the assessment of structural damage are applied to the case study area. Clausen (1989) proposed a criterion for flood damage estimation that was derived for brick and masonry buildings based on empirical data mainly from one case study, the Dale Dyke dam failure that flooded Sheffield in 1864. Further information was derived from other dam breaks and high-velocity flood events. These events only produced a few results each, but they provided confirmation of the findings from the analysis for the

Dale Dyke catastrophe (Clausen 1989). Three damage levels were distinguished: inundation damage, partial damage, and total destruction. These categories were defined in qualitative terms and described which level of structural damage they represented. Because these damage levels are linked to flood characteristics (discussed later) they can be used to distinguish different flood hazard zones with different structural damage patterns. The following criteria were proposed (see also Fig. 14):

- $v < 2 \text{ m/s}$  or  $dv < 3 \text{ m}^2/\text{s}$  yields only “inundation damage”
- $v > 2 \text{ m/s}$  and  $3 \text{ m}^2/\text{s} < dv < 7 \text{ m}^2/\text{s}$  yields “partial damage”
- $v > 2 \text{ m/s}$  and  $dv > 7 \text{ m}^2/\text{s}$  yields “total destruction”

Clausen damage criterion has been applied to Lower 9th Ward neighborhood in an attempt to investigate whether the damage observations correspond to the predictions with Clausen criterion. The  $dv$  product values are shown in Fig. 15. The damage zones that follow from Clausen’s approach and the damage observations are shown in Fig. 16. It is found that the Clausen criterion, including the velocity and depth–velocity thresholds, did

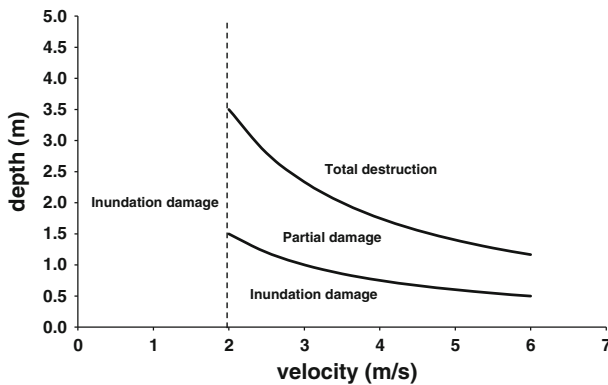


Fig. 14 Clausen structural damage criterion for brick and masonry buildings (Clausen 1989)

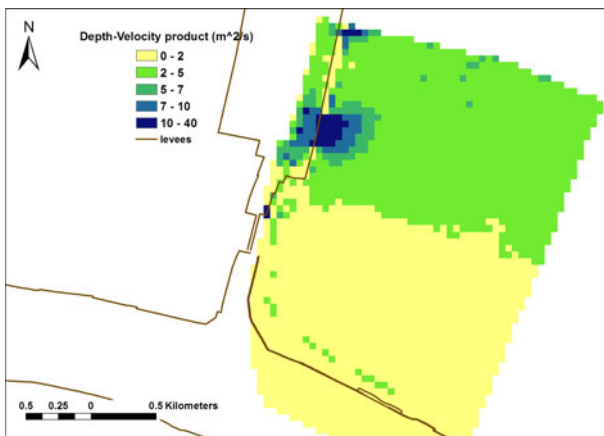
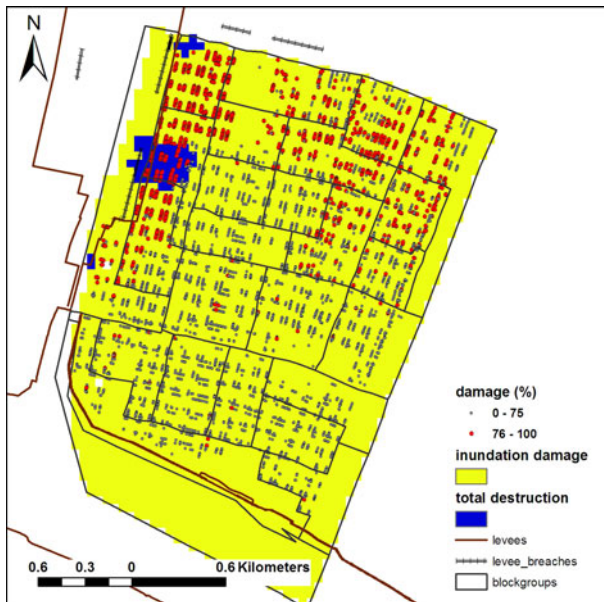


Fig. 15 Depth–velocity product values for Lower 9th Ward neighborhood



**Fig. 16** Clausen's criteria applied to Lower 9th Ward neighborhood

not accurately predict the economic damage observations of Lower 9th Ward. In particular, the second damage category of “partial damage” is not present in the developed map because the velocity threshold of 2 m/s is only exceeded when the depth–velocity product is larger than 7 m<sup>2</sup>/s.

### 5.3 Alternative approach for damage assessment based on the depth–velocity product

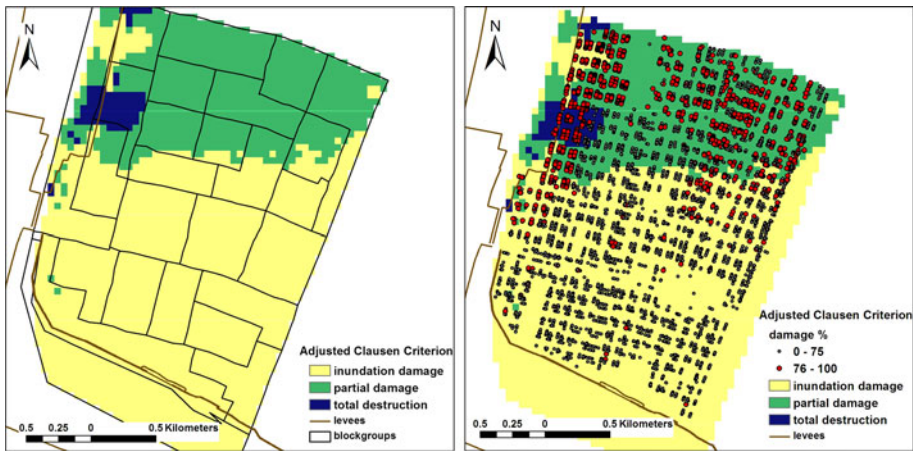
Because of the poor relationship between the observed damage and the predicted damage with Clausen criterion, an alternative criterion is proposed. It includes the depth–velocity product as the only variable. The thresholds between the categories have been chosen in such a way that a better (visual) resemblance between the observations and the prediction of the damage criteria is obtained. This approach is indicated as the adjusted Clausen criterion, and the following damage categories and threshold values are used:

- $dv < 3 \text{ m}^2/\text{s}$  yields only “inundation damage”
- $3 \text{ m}^2/\text{s} \leq dv < 7 \text{ m}^2/\text{s}$  yields “partial damage”
- $dv \geq 7 \text{ m}^2/\text{s}$  yields “total destruction”

This alternative approach gives a clear distinction of different flood hazard zones based on the depth–velocity product (see Fig. 17, left).

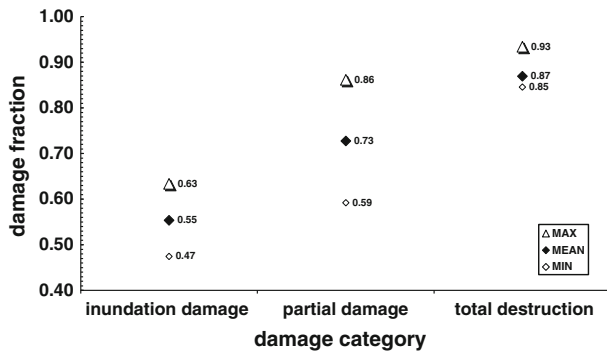
The right part of Fig. 17 shows the three zones and the dots of the damage observations. It can be observed that the spatial distribution of the observations with high damage values (>75%) does not fully correspond to the zones that are obtained by using the adjusted Clausen criterion. Especially, in the eastern part of the area, many observations with high damage values are located in the “inundation damage” and “partial damage” zones. Nevertheless, Fig. 18 shows that there is a clear difference between the average damage





**Fig. 17** Adjusted Clausen criterion applied to Lower 9th Ward neighborhood (*left*) and comparison with damage observations (*right*)

**Fig. 18** Damage value averaged over blocks for the three zones distinguished in the adjusted Clausen criterion



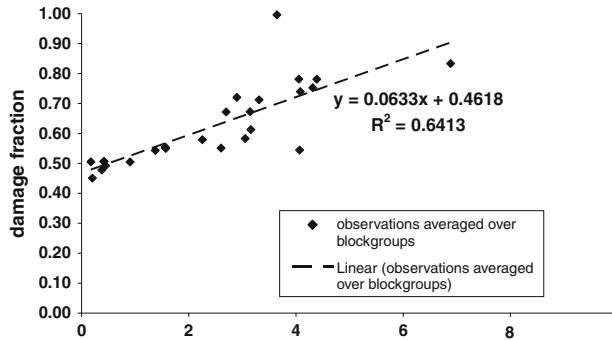
percentages for the three zones. The highest average damage value is found for the total destruction zone. This approach could be useful to determine the extent of flood damage and distinguish the main damage zones for an area affected by flooding due to breaching of flood defenses.

#### 5.4 Analysis of the relationship between the depth–velocity product and damage for the Lower 9th Ward neighborhood

In this section, the relationship between the depth–velocity product and the damage percentage is further analyzed for the Lower 9th Ward neighborhood. Figure 19 shows the relationship between the damage percentage and the depth–velocity product at the block group level ( $R^2 = 0.64$ ). Analysis at the more detailed block level resulted in a similar relationship, but the value of the correlation coefficient was lower ( $R^2 = 0.35$ ).

The relationship in Fig. 19 is based on the product of depth and velocity and thus shows a linear trendline. However, other non-linear combinations of depth and velocity are possible and can be related to the damage level. Several types of statistical distributions

**Fig. 19** Relationship between depth–velocity product and economic damage estimates over block groups



**Table 2** Analysis of the relationship between depth and velocity and the damage fraction for the Lower 9th Ward neighborhood

	Number of observations	A	B	C	R <sup>2</sup>
Block group	25	0.422	0.075	0.682	0.654
Block	394	0.457	0.063	0.654	0.364

were investigated. The least square method was used for the estimation of the distribution parameters. The following type of function resulted in the best fit:

$$D = A + Bdv^C \tag{3}$$

where  $D$  damage fraction [–];  $d$  water depth [m];  $v$  velocity [m/s];  $A, C$  constants [–];  $B$  constant [ $s^2/m$ ].

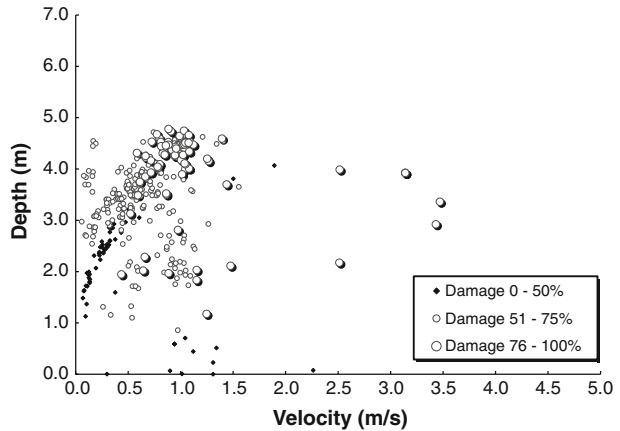
The results for the two spatial aggregation levels (block group and block) are shown in Table 2.

Table 2 shows that the derived damage relationships results in similar values for the constants, and thus they show the same trend at different scale levels. In that way, the datasets are consistent. As will be discussed further in Sect. 6.1, a more detailed analysis results in a lower correlation value between predictions and observations.

In order to visualize the effect of the combination of water depth and flow velocity on damage observations, the different damage categories (0–50, 51–75, 76–100%) are plotted as a function of depth and velocity in Fig. 20.

The figure shows that higher damage values are associated with high depth–velocity combinations. The graph includes the observations for the Lower 9th Ward neighborhood. If the observations for the Central polder would be added to the graph, most of them would be in the lower left side of the figure (i.e. in the area approximately bounded by the values  $d = 3$  m and  $v = 0.5$  m/s). Most of the block groups in the Central polder were characterized by depth values below 3 m and low velocities (see also Figs. 4, 5). As most of the observations for the Central polder had damage levels below 50% this corresponds to the observation from Fig. 20 for the smaller damage values (<50%). The figure shows that, although the main damage categories show some clustering, there is not a very strong or direct relationship between the flood characteristics and damage level.

**Fig. 20** Damage values for the Lower 9th Ward (averaged by block) as a function of water depth and flow velocity



## 6 Discussion

### 6.1 Influence of spatial aggregation level on damage analysis

In the previous sections, relatively weak relationships between flood characteristics and economic damage were found. Similar results were obtained in earlier assessments of economic damage due to floods in Germany in 2002 (Merz et al. 2004; Thielen et al. 2008).

The relationship between flood depth and damage percentages has been analyzed at different spatial aggregation levels (block group, block). Further analysis of the presented results showed that a higher spatial level of detail resulted in a lower level of correlation between predictions and observations, both for the analysis based on depth (Sect. 4) and depth–velocity (Sect. 5.3). At a high level of detail and for a limited sample size of buildings the variations in building damage may be considerable. If the sample size becomes larger, variations are averaged out.

This finding could have implications for the use of stage damage functions that are only based on flood depth for damage prediction. There is clearly not a one-to-one relationship between flood depth and damage percentage, especially at a high spatial resolution. Thereby, it is expected that the application of stage-damage function to individual buildings or small clusters of buildings does not give adequate results. If the considered area becomes larger, the relationship between flood characteristics and damage percentage improves. Thus, stage damage functions may still be useful to estimate damage for larger areas with many buildings. Merz et al. (2004) also concluded that the uncertainty of damage estimates decreases with an increasing number of flooded buildings.

### 6.2 Influence of other factors on damage

The quantitative analyses in this article have been limited to flood depth and flow velocity. In this section, the possible influence of other groups of factors is discussed.

First, inconsistencies in recording/reporting the direct damage to buildings in the site inspections may have resulted in differences in damage percentages between buildings with a similar damage level. As presented results were averaged over multiple buildings, this is not expected to be a major factor.

Second, other flood characteristics than flood depth and flow velocity could be relevant for damage processes. The impacts of debris and local waves could lead to structural damage. Water and air temperature and possible contamination are relevant for the damage to the interior of the building (FEMA 2006).

Third, variations in building type and properties result in differences between buildings in their resistance to withstand the flood loads. Important factors are the number of stories (one or more), the construction type, and material (wood, brick, concrete), the foundation type and the ground elevation. All these factors are likely to have affected the vulnerability of residential buildings to the flood effects.

Roos et al. (2003) investigated the resistance of different building types (wood, brick, concrete) by means of structural calculations and showed that wooden constructions are the most vulnerable. The foundation type affects a building's resistance to withstand higher flow velocities. Most of the residential buildings in New Orleans, especially in the neighborhood with the highest damage (the Lower 9th Ward), were wooden, the so-called "shotgun type" houses, with limited resistance to the flood impacts.

Also, the building's elevation has an important effect on the level of flooding and the consequent damage. Many buildings in New Orleans had some elevation based on flood insurance requirements, and this could limit the level of flood and consequent damage. According to FEMA (2006), most of the historic homes were elevated several feet, while newer constructions were constructed on slab-on-grade foundations with small elevations. Direct data regarding the distribution of different housing types in various areas of the city are not available. As the building characteristics are expected to be the most important determinant of the resistance, this is a recommended direction for further work. It could also be investigated whether differences in damages and housing types were related to socio-economic characteristics of the population.

## 7 Conclusions and recommendations

In this article, the relationship between flood characteristics and damage to residential buildings due to flooding of New Orleans after hurricane Katrina has been investigated. The main findings can be summarized as follows:

- Differences in observed damage distributions between the studied polders can be related to differences in flood conditions. The highest damage percentages and structural damage mainly occurred in areas where higher flow velocities occurred, especially near the breaches in the Lower 9th Ward neighborhood. Due to the approach that was used for damage quantification, buildings that sustained structural damage, had damage levels higher than 50% of their market value.
- Application of the Clausen damage criterion (Clausen 1989) to the flooding of the Lower 9th Ward neighborhood did not result in an accurate hind cast of the observed flood damage.
- An alternative approach has been proposed that could be used to distinguish three different damage zones based on the combination of water depth and flow velocity. There appeared to be clear differences between the average, observed damage values in the three zones. This approach could be useful to determine the extent of flood damage and distinguish the main damage zones for an area affected by flooding due to breaching of flood defenses.

- No clear one-to-one relationship between flood characteristics and the exact values of observed damage percentages was found. This has also been concluded in earlier work based on damage observations for other flood events (Merz et al. 2004). Thereby, it is expected that the application of stage damage functions to individual buildings or small clusters of buildings does not give adequate results.
- The spatial level of detail of the analysis is a determining factor for the correlation between predictions and observations. The smaller the spatial unit of the analysis the poorer the relationship between flood characteristics and damage. This also implies that damage criteria that are derived on this type of data should not be used at a too high level of spatial detail, e.g. for individual structures.

Based on this study, the following recommendations are made:

- Given the relative weakness of the observed relationship between flood characteristics and damage percentages, it is recommended to further investigate the application of stage-damage functions. In this context, it is also relevant to further investigate the adequate spatial aggregation level of damage analysis in relation to the variations in the data that were used for the derivation of the stage-damage functions.
- It is recommended to investigate the derivation and rating methodology of the damage dataset, in order to verify the quality and reliability of the data. A review and verification of the dataset (Skinner 2006) revealed several issues that could affect the quality and consistency of the data.
- It is recommended to collect further information about the variation in building types, structures, and materials. An analysis of the damage data according to the building type and the structure may lead to better results.
- The analyzed damage estimates primarily refer to economic flood damage. In further work, it would be interesting to investigate whether a more specific relationship between flood characteristics and structural damage level could be found.
- It is recommended to further investigate the relationship between damage and loss of life. The large number of fatalities near the breaches in the Lower 9th Ward neighborhood appears to be related to the large number of collapsed buildings in the area and the consequent loss of shelter (Jonkman et al. 2009).
- It is recommended to apply existing damage models, such as FEMA's HAZUS model, to provide an estimate in hindsight of the damage in New Orleans due to hurricane Katrina. Comparison of the predicted and observed data could be used to improve the damage models.

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