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Risk to life due to flooding in post-Katrina New Orleans

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Abstract

After the catastrophic flooding of New Orleans due to hurricane Katrina in the year 2005, the city's hurricane protection system has been improved to provide protection against a hurricane load with a 1/100 per year exceedance frequency. This paper investigates the risk to life in post-Katrina New Orleans. In a risk-based approach the probabilities and consequences of various flood scenarios have been analyzed for the central area of the city (the metro bowl) to give a preliminary estimate of the risk to life in the post-Katrina situation. A two-dimensional hydrodynamic model has been used to simulate flood characteristics of various breaches. The model for estimation of fatality rates is based on the loss of life data for Hurricane Katrina. Results indicate that – depending on the flood scenario – the estimated loss of life in case of flooding ranges from about 100 to nearly 500, with the highest life loss due to breaching of the river levees leading to large flood depths. The probability and consequence estimates are combined to determine the individual risk and societal risk for New Orleans. When compared to risks of other large scale engineering systems (e.g. other flood prone areas, dams and the nuclear sector) and acceptable risk criteria found in literature, the risks for the metro bowl are found to be relatively high. Thus, despite major improvements to the flood protection system, the flood risk of post-Katrina New Orleans is still expected to be significant. Effects of reduction strategies on the risk level are discussed as a basis for further evaluation.

1 Background and scope

Hurricane Katrina struck the southern Gulf Coast of the US on 29 August 2005. The surge caused by the storm overwhelmed the existing flood protection of the city of New Orleans, Louisiana leading to one of the worst natural disasters in American history. Catastrophic flooding throughout the city led to economic losses of more than 20 billion dollars, and over 1100 people lost their lives in the state of Louisiana; many in the flooded area of New Orleans (Jonkman et al., 2009b). In the wake of the event, the US government committed to provide New Orleans flood protection from a hurricane with a 1/100 per year exceedance frequency, and since then, massive effort, resources and expertise have been employed to do so. However an important discussion remains regarding the residual flood risk associated with the upgraded protection system. This is not only an issue for New Orleans, but also for other flood prone areas in the US (Jonkman et al., 2012) and in other parts of the world (Hallegatte et al., 2013).

Risk is generally considered to be a function of the consequences and probability of an undesired event. It is commonly characterized in engineering fields, such as nuclear and chemical engineering, to inform decision making regarding hazardous events. As flooding can be considered a large consequence–low probability event, the same approaches can be applied in this context (Vrijling, 2001), where the consequences and frequencies of a potential flood event are used to inform decision making.

New Orleans' risk of flooding will increase in the future due to many factors including regrowth of the population and economy as well as physical factors such as sea level rise and ground subsidence. The specified protection level of the upgraded system has been based on existing national flood management policy, however a risk informed approach to flood protection allows safety and economic considerations to be included in floodplain management. In such an approach, the flood protection is assessed as a system where the weaker areas can be identified and risk reduction measures systematically analyzed to manage and mitigate the overall risk. While flood risk management is a complex balance of social, political and economic factors, risk evaluation can provide technical basis for decision making.

In risk evaluation, the risk to human life, property, environment, or other risk dimensions can be quantified. Considering the catastrophic loss of life caused by Hurricane Katrina and flood events in other parts of the world, the risk to life is an important component in determining levels of protection and flood risk management strategies. The objective in this study is to assess the risk to life associated with the upgraded flood protection of New Orleans in order to provide insight into the flood risk level of the city.

This work adds to the existing body of work related to flood risk studies in general and specifically for New Orleans (IPET, 2009a; Jonkman et al., 2009b). Specifically referenced in this paper is the work of the Interagency performance evaluation taskforce, or IPET. This assembly of academia, industry and government was established after Hurricane Katrina to conduct an in depth analysis of the city's protection system. The IPET effort included a detailed reliability analysis of the upgraded protection system and results include economic and life loss consequence estimates for various event frequencies. This article supplements the IPET work and differs in various ways. The analyses in this study are based on two-dimensional flood simulations and empirical life loss models based directly on data from Katrina, whereas IPET used other modelling approaches (see IPET, 2007). Also, the risk to life of the upgraded protection system is evaluated in this study by comparing results to acceptable safety standards found in literature and applied in other engineering sectors. Further, risk reduction measures are analyzed to show the application of risk evaluation in determining the most effective measures. Finally the combined risk of both hurricane and riverine flooding are considered in this study. A riverine event, while a low probability event is expected to result in disastrous consequences.

To achieve the objectives of this study, a general risk assessment, consisting of the identification, quantification and evaluation of risk, is carried out. The steps of such an assessment are summarized in Fig. 1, and the outline of this article follows these steps. The first step is the definition and analysis of the system, in this case the New Orleans flood protection system, and the analysis of the potential hazards (Sect. 2). Next, in Sect. 3, a quantitative risk estimate is accomplished through the analysis of possible flood scenarios and their likelihoods and consequences. In Sect. 4, the quantified risk estimate is evaluated and compared to limits of "tolerable" or acceptable risk and risks in other sectors. Finally, risk reduction is discussed in Sect. 5 where measures to mitigate risk are briefly analyzed. Concluding remarks are given in Sect. 6.

2 The New Orleans system

2.1 General

The unique natural environment surrounding New Orleans makes the city highly vulnerable to flooding. Figure 2 depicts the city's surroundings and the upgraded system of flood protection. Located in the deltaic plain of the Mississippi river, the initial city settlement was built on the high banks of the river. Over time, however, the city expanded out into the lower lying marshland, draining the land to support the growing urbanization. Combined with loss of river sediment and other factors, this has led to significant ground subsidence. Almost half of the city now sits below mean sea level, in some areas up to 3 m. Current annual subsidence rates average 5–7 mm per year (Campenella, 2006). Further, the city is bordered by wetlands to the south which serve as a buffer to the coast. The ongoing erosion of these coastal wetlands however is increasing the city's proximity to the Gulf of Mexico over time.

As a low lying area surrounded by water, the city can be flooded by multiple sources. In this assessment, the risk of flooding due to a hurricane surge event and a high river flood event are assessed. While flooding can also occur due to an extreme rainfall event, it is not considered here as it is assumed the consequences are less catastrophic Also, wind-related effects of hurricanes can lead to damages and some fatalities, but are not considered in detail here as it is expected that the number of wind-related fatalities is smaller than flood events. Storms in the past with comparable strength but less flooding resulted in much fewer fatalities. For example, Hurricane Frederic (1979) occurred in the same area and was of similar strength (category 3). It caused 5 fatalities. Hurricane Betsy was also of similar strength and led to less extensive flooding than Katrina in mainly the eastern parts of the city, and causing 76 fatalities (FEMA, 2006; pp. 1–28).

2.1.1 Flooding due to a hurricane surge

The warm temperatures of the Gulf of Mexico during summer months facilitate the formation of tropical storms whose low pressure elevates the sea surface while storm winds push the water up against the coast. While initial inhabitants built private levees to address flood issues from riverine and topical storms, the federal flood control act of 1946 authorized levees to be constructed along Lake Pontchartrain. The impacts of Hurricane Betsy in 1965, which included major flooding and significant loss of life, prompted Congress to authorize a hurricane protection system of levees, floodwalls, and floodgates. Construction for this system began in mid 1980's and was expected to be completed in 2015.

The impact of Hurricane Katrina in 2005 however, was no match for the existing hurricane protection system.

After moving over Florida as a hurricane 1 on the Saffir-Simpson scale on 25 August, Katrina intensified over the Gulf of Mexico until the central pressure reduced to 902 mb and sustained wind speeds reached 145mph. By 28 August, the storm had become a category 5 hurricane with hurricane force winds that extended 90 nautical miles from the eye, or center of the storm. Katrina's intensity and unprecedented size brought the highest surge ever recorded on the North American coast at an elevation of 27.8 feet (8.5 m) NAVD88, recorded 100 miles to the east of New Orleans at Pass Christian, Mississippi. The surge caused massive flooding and devastation along a 170 mile (approximately 270 km) stretch of the US Gulf, and the entire coastline of the state Mississippi suffered massive destruction due to surge flooding (Jonkman, 2009b).

The storm made landfall as a category 3 to the east of the city of New Orleans, pushing the water that had build up against the east side of the river delta into the city, The still significant winds pushed the massive surge into the city, overtopping and failing levees and floodwalls. More than 50 breaches were documented in the flood protection of the city system, most due to the overtopping of levees made of hydraulic fill (Sills et al., 2008). However, some floodwalls failed prior to being overtopped due to other (geotechnical) failure modes. For example, sliding due to unstable foundation soils, piping and seepage, and high uplift pressures all caused failure of floodwalls. The consequential flooding left over 80 % of the metropolitan areas under water, roughly 260 km^2 of the city. The complete dewatering of the city took approximately 6 weeks.

It has been estimated that 80 % of the city's residents evacuated prior to the storm (Boyd, 2012) leaving those that remained to shelter in place. After the storm had passed, a massive recovery effort was undertaken to rescue those trapped by the flood. Thousands of people were rescued from roofs, attics, hospitals, nursing homes and other flooded areas by emergency crews. This led to a delay of several days in the evacuation of the city's shelters and conditions in the shelters soon deteriorated due to heat and lack of supplies. Three days after Hurricane Katrina made landfall, buses finally began evacuating people out of the city.

2.1.2 Flooding due to a river flood wave

The contribution of risk of flooding to New Orleans due to a high river event is also considered in this study. The Mississippi river drains the third largest river basin in the world, 3 224 550 square kilometers and 40 % of the continental US. Prior to manmade levees, the river's seasonal high flows would overflow the river banks and inundate the floodplain. As the city of New Orleans grew, private levees were built to protect residents form river floods. But in 1927, a year of heavy rain led to extreme flood flows. 70 000 square kilometers of the Mississippi floodplain were inundated including the alluvial valley. In New Orleans, fear of the city center flooding led city officials to dynamite levees which protected southern, poorer areas of the city. In total, the floodwaters displaced 700 000 residents and claimed an estimated 250 lives. The events of 1927 led to the highly controlled and federally mandated Mississippi river levee system, the longest flood protection system in the world. The river level at New Orleans is regulated by a system of upstream spillways. The system was most recently tested in 2011, when record high stages initiated the use of emergency levees and bypass structures to divert flow and control water levels in the lower delta.

2.2 Study area and system boundaries

Only a portion of the city of New Orleans is assessed in this article, the area of densest population and greatest economic value. This area, which is referred to as the “metro bowl”, is roughly 100 km^2 (40 square miles) and home to a post-Katrina population of roughly 221 000 people (Census Bureau, 2010). Hydraulic boundaries of the studied area consist of Lake Pontchartrain to the north, the Mississippi river to the south, and the IHNC or the Inner Harbor Navigation Canal to the east. The western boundary of the studied area is a municipal boundary. The system boundaries of the metro bowl can be seen in Fig. 3. Lake Pontchartrain to the north of the metro bowl is connected to the sea to the east, and therefore subject to the effects of storm surge. Pre Katrina lake protection included floodwalls along the city’s drainage canals, which extended from the city center and emptied into the lake. During Katrina, an extreme lake surge 2.5 m above normal water level entered the canals, failing the canal floodwalls and flooding the city center. Upgraded protection measures include the installation of pumping stations where the canals meet the lake effectively shortening the coastline, preventing potential lake surge from filling the canals. To the east of the metro bowl is the man made shipping canal, the Inner Harbor Navigation Canal (IHNC). The canal connects to the Mississippi river at the south, to the lake at the north, and to the confluence of two navigable waterways at the east. Prior to the upgraded system, the IHNC was highly vulnerable to extreme surges due to this confluence, as the surge could be funneled up in to the canal. During Katrina, surge levels reached 14ft (4.25 m) NAVD88 in the canal (IPET, 2007), leading to disastrous flooding. Since the storm, two new barriers have been constructed which significantly reduce the opportunity for surge to enter the IHNC. These are the lake borgne barrier, constructed near the confluence of the two waterways at the east of the IHNC, and the seabrook barrier, constructed at the north end where the canal meets the lake. Finally, the river boundary to the south is affected by both riverine flood events and hurricane induced surges that travel up the river, so flooding due to both hydraulic mechanisms is considered. During Katrina, the river stage reached 12 feet (3.24 m) NAVD88 at the river gage at the location of the city (see Fig. 4). Design criteria for river protection include considerations for both hydraulic loadings.

3 Quantitative flood risk analysis for New Orleans

In this section, the approach and main assumptions for assessing the system reliability, flood effects and consequences are described. This is followed by a discussion of results of the quantitative risk analysis. Kaplan and Garrick (1981) define risk as a set of scenarios, each of which has a probability and a consequence. In this study a simplified scenario-based and somewhat simplified approach has been adopted to estimate the risk. The system reliability is estimated based on design criterion of the upgraded protection in combination with expert opinion. A failure frequency can be assigned to each scenario to estimate the overall risk.

3.1 System reliability

To determine the reliability of the considered system, a complete probabilistic analysis should be carried out to consider all possible strength parameters of the system and the possible loads which act on the system; the strength of the system would be characterized by potential failure mechanisms of the protection structures such as overtopping, sliding and piping (see Fig. 5). Such types of analyses have been made for the New Orleans (IPET, 2009a) and Dutch levee systems (Jongejan et al., 2012). However, for simplification in this work, the reliability is based on the system design.

Design elevations for the updated hurricane protection have been determined by limiting the allowable overtopping rate for the 1 % hurricane surge and associated waves. While there is still the potential for failure due to other (geotechnical) failure modes, robust design specifications such as seepage and stability for example, have also been applied so that failure due to these failure modes is assumed to be substantially smaller than for an overtopping failure. So while the USACE design guidelines do not consider the cumulative failure probability of all failure mechanisms, the resulting design is expected to have a high degree of conservatism (USACE, 2007) and failure probabilities applied in this study are based the overtopping failure mode.

To determine the overall system failure probability, the flood protection system is described as a series system of elements where the failure of any individual element will lead to flooding of the protected area. During a storm event, loading of the system is highly dependent, so each defences' resistance to overtopping is dependent (other failure mechanisms would be less dependent, but they are not considered here). As such, a first approximation for the system failure due to a hurricane load is estimated to be 1 %, (but again, more research in the form of full reliability analysis is needed). Based on this assumption, each element is then assigned a failure frequency.

For example, for the lake protection, it is expected the upgraded design can withstand the 1 % event with some additional margin. Therefore an estimate for failure probability of the lake protection is determined to be 1/150 per year. Along the IHNC, the potential for extreme surge loading has been greatly reduced due to the two new surge barriers. Thus it was determined the most probable failure would be conditional upon the failure of a gate closure. This combined event of high water and the failure of a gate to close is estimated to have a probability of 1/500 per year.

And while the river protection in the region of the delta is designed to consider both riverine and hurricane loading, the river levees at the New Orleans metro bowl are currently governed by riverine design criteria. The updated storm surge analysis results show that the 1/1000 per year water loads due to storm surge travelling up the river are comparable to the current riverine design water levels. Thus a 1/1000 per year failure probability is a best estimate for a river breaching due to storm surge.

Finally, for failure of the river levee due to a high river event, the design capacity of the upstream spillways must be exceeded for the water levels at New Orleans to exceed design loading. According to calculations by USACE, the estimated frequency with which river discharge exceeds the upstream spillway capacities is roughly 1/880 per year. This is used as a basis for a river levee reliability estimate of 1/1000 per year.

The relationship between element failures and the undesired consequence can be depicted in a fault tree (see Fig. 6). Each element varies from that adjacent to it such that the failure of the elements is considered independent. Correlations and dependencies between the section failure probabilities would be taken into account in a more detailed analysis. Thus the estimated total probability of failure of the defined system is approximately 1.1×10^{-2} per year (1/110 per year) since it is assumed that a failure due to hurricane surges (1/100 per year) and a failure due to high river discharges (1/1000 per year) are independent.

3.2 Development of flood scenarios

To characterize the risk and estimate the potential consequences of flooding, a number of flood scenarios have been defined. Each flood scenario refers to a breach at a certain location in the flood defence system (or a set of multiple breaches) and the resulting pattern of flooding. Scenarios are chosen such that the various potential load mechanisms, the response of the various protection elements, and a range of potential consequences due to flooding are considered.

Characteristics of a scenario include load hydrographs, breach parameters, evacuation assumptions and other factors. Hurricane frequency data is computed using a joint probability model. The joint distribution of primary hurricane storm parameters is used to determine the probabilities of a suite of synthetic storms. For more information on development of hydraulic data, see Resio et al. (2006). Surge and associated waves have been provided up to a 1/500 per year event on the lake and canal, and up to a 1/1000 per year event for surge traveling up the river. Breaches are modeled to occur when the external load exceeds the design capacity of the defense, and an average hydrograph width is estimated for each scenario based on the synthetic storm hydrograph data. Hurricane breach widths and inverts are based on post Katrina breach evidence, and riverine breach characteristics are based on literature and documented historical failures. As there is little evidence for breach development time, a simple approach is applied where simulated breaches first grow from the original bank level to ground level in two hours, and then to final width in three additional hours.

For example, the failure of the levees along Lake Pontchartrain is modeled. Two breach locations along the lake are simulated to model a range of flood extents. The breaches are modeled to occur for a load hydrograph with a 1/500 per year peak water level, as it is expected the lake protection can withstand the 1/100 per year loading with some margin. Breach widths are estimated to be 100 m and the invert of the breaches is assumed to reach adjacent ground level.

A 1D-2D SOBEK overland flow model is used to simulate the hydraulic characteristics of each scenario. The model is based on a previously developed model of the New Orleans metro area (see de Bruijn, 2006). The terrain roughness applied in the model is a Nikuradse value of 0.3, and sensitivity studies show that model results were minimally sensitive to the roughness value applied. The effects of internal drainage are not included in the model. For the catastrophic effects expected to result due to breaching, it is considered that these effects may only play a minor role in the spreading of the flood waters. The SOBEK model computes depth and velocity as a function of time, simulating the progression of flood waters and flood depth. Flood depths and extents of the scenarios, including the high river flood scenario can be seen in Fig. 7.

3.3 Determination of consequences

With the use of a life loss model, the flood characteristics are related to a mortality rate, which is the number of deaths due to flooding divided by the population exposed to the flood effects. These functions have been derived based on the observations of Hurricane Katrina (Maaskant, 2007; Jonkman et al., 2009b). For the metro bowl, two zones of flood characteristics have been distinguished which correspond to two mortality functions (see Fig. 8). Two further variables are used to estimate the life loss: the initial population and the percent of that population assumed to have evacuated. During Katrina, evacuation out of the city was estimated to be about 80 % (Jonkman et al., 2009b; Wolshon, 2006). For this study, 2010 census data is used, which results in an initial population of 221 000 for the metro bowl. An evacuation rate of 90 % is applied for hurricane and riverine flood scenarios, such that 10 % of the initial population is assumed to be the exposed population. It is expected that public awareness and access to evacuation aid has improved since Hurricane Katrina, so the assumed rates might be somewhat conservative. For a riverine event, the evacuation rate assumption should be investigated further in a more detailed analysis.

3.4 Results

Table 1 presents results for the developed flood scenarios. The second column shows the estimated failure probability of the scenario (see above and Fig. 7). The calculated mortality rate for a flood scenario depends on the number of fatalities and the size of the flooded area. Since the number of fatalities is primarily depth-dependent, mortality results range from 0.4 % for the breach at the IHNC to 2.0 % for the breach due to a high river flood event, resulting in fatality estimates in the range of 100–450. Failure of the IHNC is assumed to occur given a gate failure, therefore breaching occurs at a more frequent event than the rest of the system, and less catestrophic flood effects result. Flooding due to the high river flood event in the river is especially catastrophic as flood depths can be large and the duration of the flood wave can be up to several weeks (compared to hurricane duration of several hours). After levee breaching due to the high river event, the metro bowl is expected to continue to fill, resulting in flood depths of over 5 m in some areas. Lessons learned from Katrina and other floods shows that closure of breaches during inflow is generally not possible.

As the results are the function of assumptions used in models with various uncertainties, they give an indication of the order of magnitude of potential life loss. Sensitivity of the results to several variables is investigated. It was found that results are not sensitive to final breach dimensions as ultimate flood extents and depths will eventually match the boundary water level (de Bruijn, 2006). The load hydrograph duration for hurricane events did impact results as increased load duration leads to an increase in maximum water depths. The effect of hydrograph duration on the risk could be evaluated in further analysis. Overall however, flood extents, characteristics and resulting mortality rates of the hurricane flood scenarios are comparable to events that occurred during Hurricane Katrina. It is estimated that roughly 250 persons perished in the metro bowl due to direct flood effects during Katrina and an area with about 250 000 inhabitants was flooded (Jonkman et al., 2009b). While significant improvements have been made to the protection system, resulting in reduced failure probabilities, all flood scenarios are expected to result in catastrophic flooding of the metro bowl due to the low-lying geography of the area.

3.5 Risk quantification

Finally, risk to life is quantified by combining the probability and damage estimate of each scenario. Risk is quantified as both individual risk and societal risk, and is evaluated based on acceptable risk criteria.

3.5.1 Individual risk

While various definitions exist (Jonkman et al., 2003), individual risk can be described as the probability of death of a single person at a given location. The following formula is used to assess individual risk and takes into account the various scenarios that can affect a location and the mortality as a function of flood characteristics. For flood risk, evacuation is generally taken into account, since it is expected to have a significant effect on the risk to people. Therefore the evacuation fraction (F_E) is also included in Eq. (1).

$$\mathrm{IR}(x,y) = \Sigma P_i, F_{\mathrm{D}|i(x,y)}(1 - F_\mathrm{E}) \quad (1)$$

Where $\mathrm{IR}(x,y)$ = the individual risk at location (x, y) [yr^{-1}]; Pi = the probability of occurrence of flood scenario i [yr^{-1}]; $F_{\mathrm{D}|i(x,y)}$ = the mortality at location (x, y) given flood scenario i [–]; F_E = evacuated fraction of the initial population [–].

Figure 9 shows the results of individual risk for the metro bowl. The metro bowl largely has an IR value of greater than 10^{-5} per year (i.e. 1/100 000 per year) with a maximum value of 5×10^{-5} per year. As the IR is a function of a depth dependent mortality function, the risk largely corresponds with the area topography.

3.5.2 Societal risk

Another way of quantifying risk is the societal risk. It is defined as the probability of exceedance (in a year) of a certain number of fatalities due to one event in a given population or area. This metric also accounts for evacuation as it is a function of the population directly exposed to the flooding. Depiction of societal risk is commonly accomplished with an FN curve or a frequency–number curve as seen in Fig. 9. The curve plots the probability (per year) that *n* fatalities are exceeded. The intersection with the y-axis is the cumulative probability of the scenarios in Table 1.

The studied area's overall flooding probability is $1.1 \times 10^{-2}\,\mathrm{yr}^{-1}$ (i.e. 1/110 per year). The intersection with the x-axis is the consequence result of the scenario with the largest consequences, roughly 450 fatalities. Probability and fatality estimates for the scenarios are combined to determine the annual expected number of fatalities, about 2 fatalities/year.

The FN curve resulting from this study is plotted against an FN curve based results from the IPET risk study in Fig. 10 (IPET, 2009b). IPET loss of life estimates for the New Orleans metro bowl are plotted for the 2 %, 1 % and 0.2 % events for the 2011 upgraded protection system and assume a 0 % pumping capacity for the 0.2 % event, and 100 % pumping capacity for the 2 % and 1 % event. The IPET results consider risk due to rainfall flooding, but do not include risk due to a river flood. In the IPET results, rainfall flooding is shown to be a significant risk contributor for the 0.2 % and 1 % events, thus results of these events assuming the 100 % pumping capacity are plotted. However for the 0.2 % event, the result assuming the 0 % pumping capacity is plotted, as no significant pumping is expected when levees breach.

IPET life of loss estimates apply a pre-Katrina exposed population and an 80 % evacuation rate (IPET, 2007). The larger initial population and smaller evacuation rate estimate may explain the somewhat higher loss of life estimates by IPET for low probability events than the results of this study. Despite these variations in assumptions however, a comparison of FN results can be made and both societal risk estimates are in the same range.

4 Risk evaluation and risk reduction

The results are indicative, but preliminary estimates of the risk to life of the New Orleans metro bowl in the post Katrina situation. The estimated risk is evaluated by comparison with criteria for acceptable risk found in literature and risks for other systems. Two main sources of evaluation criteria include a framework developed by Vrijling (1995), and proposed levee safety reference guidelines of the US Army Corps of Engineers (USACE, 2010).

4.1 Individual risk criterion

Acceptable individual risk considers the viewpoint of the individual who weighs the risks against benefits before undertaking an activity (Vrijling et al., 1995). As a starting point for an acceptable individual risk, Vrijling conducted an analysis of fatality statistics and concluded the probability of dying to non-voluntary activities should be one or two orders of magnitude lower than the average probability of death for younger persons. In western world, this is in the order of magnitude of 10^{-4} per year, resulting in the following equation to describe an appropriate individual risk level:

$$\mathrm{IR} < \beta 10^{-4} \quad (2)$$

Where β is the policy factor and represents the level of voluntariness of the activity (greater voluntariness corresponds to a higher β value). Flood protection in urban areas is considered to be a relatively involuntary situation such that a β value of 0.1 can be applied, resulting in an IR limit of 10^{-5} per year. This value is also considered for flood protection in the Netherlands. When this framework is applied in less voluntary applications, for example in industrial safety, a risk limit of 10^{-6} per year is determined to be acceptable (Vrijling, 2011).

Recent USACE levee safety criteria define tolerable risk as "the risk that society is willing to live with so as to secure certain benefits". Based on existing risk limits applied in industry such as dam safety, chemical contamination and land use planning, the USACE proposed a individual tolerable risk limit of 10^{-4} per year for initial considerations. It was agreed this value had achieved consensus among government and private sectors institutions engaged in safety management (USACE, 2010). While 10^{-4} per year is more risk averse than that proposed by Vrijling, an additional consideration discussed in the USACE guidelines is the use of a buffer zone to characterize between "tolerable" and "acceptable" risk criterion. This buffer zone falls between 10^{-6} and 10^{-4}, and is known as the "ALARP" zone, the "As Low As Reasonably Practical" zone. The range provides for the many complex factors involved in determining acceptable risk such as cost effectiveness and societal concern (see Fig. 11).

When assessing the individual risk for New Orleans, the risk is relatively low in comparison with the probability of a car accident for example (10^{-4} per year), and falling within the tolerable risk range of the USACE (between tolerable and acceptable risk). However, the majority of the metro bowl results in IR values higher than 10^{-5} per year, exceeding the acceptable level of individual risk proposed by Vrijling.

4.2 Societal risk criterion

Individual risk reflects the individual perspective. In addition, society as a whole is averse to large, multi-fatality events. Such events provoke a greater social political response (Baecher, 2009). In order to evaluate societal risk, the FN curve representing the societal risk is plotted against an acceptable limit line. Again based on accident statistics, the threshold for a national, socially acceptable societal risk level in the

Netherlands has been proposed by Vrijling:

$$1 - F(n) < C_N / n^{\alpha} \tag{3}$$

Where $F(n)$ = cumulative distribution function of the number of fatalities; C_N = a constant that determines the vertical position of the limit line [yr^{-1} $\text{fat}^{-\alpha}$]; α = risk aversion coefficient and slope of the limit line.

The height of the limit line (C_N) and the value of risk aversion coefficient are subject to academic and societal discussion. In previous studies values of $C_N = 11$ and $\alpha = 2$ have been proposed for the situation in the Netherlands (Jonkman et al., 2008; Vrijling et al., 1998).

The proposed USACE criteria for societal risk for levees is once more based upon existing acceptable risk limits applied in other sectors, largely on the US Bureau of Reclamation's dam safety program (USBRC, 2003, see Fig. 12). The limit line applies a base point of the annual probability of 10^{-4} per year corresponding to the loss of life of 10, and applies a limit line slope of $\alpha = 1$ for acceptable risk associated with flood protection. The risk aversion coefficient α reflects the degree to which society is averse to the large multiple fatality accidents. The USACE applies a slope of 1, placing equal weight on exceedance probabilities and numbers of fatalities, resulting in a more risk neutral approach than the Dutch approach which uses a slope of $\alpha = 2$ to reflect risk aversion.

Finally, comparison of the societal risk can be made with that of other sectors, such as is seen Fig. 12. Here, failure probability and fatality data of several industries is plotted (Lambert and Associates, 1982). By doing so, insight into the relative magnitude of the risks in different domains and magnitude of risk to life of the city of New Orleans can be gathered. It is noted however, that the current study considered only the metro bowl. Not all Katrina related fatalities occurred in this area. If the risks for the current situation are assessed taking into account other areas (parts of New Orleans and Louisiana) that would be affected by hurricane induced flooding, the loss of life and risk estimates for the current situation would be higher.

When results of this study are plotted against proposed limit lines, it is seen in Fig. 13 that the societal risk for New Orleans exceeds criterion limits, most notably so when compared against criterion found in the updated USACE tolerable risk guidelines for dams. As the proposed USACE limit line is based on dam safety criteria, a relatively involuntary activity with perhaps little direct benefit to those affected by the risk (Vrijling, 1995), the USACE limit criterion is anticipated to be conservative for a levee application. A further discussion of the accepted failure probabilities according to the various perspectives is included in the next section.

4.3 Effectiveness of measures to reduce risk

The results of this study can also be used to analyze the effects of various risk reduction strategies in a systematic and consistent way. Risk reduction measures can be categorized into measures that reduce event probability and that reduce event consequences.

Measures that reduce the event probability include strengthening and upgrading of the levees and measures that reduce the hydraulic load on the system, such as barrier islands, wetland restoration and river diversions. The protection level or reliability required for the New Orleans metro bowl in order to comply with tolerable risk criteria can be determined (Table 2). This shows that most of the criteria for individual and societal risk would lead to protection levels of 1/10 000 per year or higher. It is interesting to note that the 1/10 000 per year protection level is also adopted in the Netherlands for some of the flood prone areas with the highest values and population densities.

The risk reducing effect of various measures is difficult to quantify, but the developed risk framework can be used as basis. A detailed assessment of the effects of measures is outside the direct scope of this paper, but to demonstrate the application and considerations a preliminary analysis of the risk reduction of some measures is presented as a basis for further discussion and elaboration. Strategies for which risk reduction effects have been discussed include: increased protection, elevation of homes, improved evacuation and relocation of population to higher areas.

The cost effectiveness of the risk reducing measures related to life loss reduction can be evaluated by quantifying the CSX value, or the cost of saving an extra statistical life. This index is a ratio of the cost of each proposed measure divided by the risk reduction provided by the measure:

$$\mathrm{CSX} = I/\Delta E(N) \tag{4}$$

Where: CSX = the cost of saving an extra statistical life per year ($/Fat/yr), I = investment ($), and $\Delta E(N)$ = change (reduction) in expected number of fatalities (fat yr^{-1}).

The lower the ratio between the investment and the saved lives, the more cost effective the measure. Results of the analysis show that increasing evacuation is the most cost effective as it limits the exposed population at a relatively low cost. A 1/500 per year protection level is the next most cost effective followed by the elevation of homes. Finally, the reductive effect of relocating the population within the metro bowl is minimal due to the large flood extents of the scenarios. It is noted that some measures, such as increased evacuation are effective to reduce the risk to life, but would not limit other types of risk, such as the economic risk that would result from widespread flooding. Further elaboration of the risk framework and measures is needed to come to a realistic assessment of risk reduction effectiveness.

5 Concluding remarks

An evaluation of the risk to life for the city of New Orleans has been carried out. Results show that the risk to life, while considerably reduced from the pre-Katrina status (see also IPET, 2009b), is still significant. The quantified individual risk to life exceeds the criterion proposed by Vrijling et al. (1995) and falls within the range of tolerability criteria defined by the USACE (2010). The quantified societal risk exceeds proposed criteria found in literature and is higher than acceptable societal risk quantified in other sectors. Thus, while there is not a consensus on an acceptable risk to life criteria, the post

Katrina risk to life for New Orleans is still relatively high. Investigation into the quantified effects of risk reduction strategies show that evacuation can be effective to reduce life loss. Evacuation and various other measures can be considered as part of a risk management strategy for New Orleans, see also Lopez et al. (2009). Based on these results and anticipating increased flood risk in the future, further discussion regarding the management and reduction of flood risk for the city is recommended.

Efforts to reduce risk should continue to be investigated and the results of the risk assessment study can also be used for risk communication to affect risk awareness. Finally, the application of risk standards and acceptable risk criteria at a national and local level are anticipated to be an important aspect in the future of flood risk management.

The results presented have been based on only a limited number of flood scenarios. For a more complete evaluation, it is recommended to include a more complete set of flood scenarios to better represent possible load situations, breach combinations and flood conditions. Reliability estimates are first order and preliminary and expected to be conservative. A more complete reliability analysis should be carried out to verify and improve these estimates. As this study has considered only a portion of the city, the approach should be applied to the remaining metropolitan areas of New Orleans for a more complete risk assessment. Reduction measures that reduce the hydraulic load can be analyzed in greater detail and quantified. A more comprehensive risk analysis can be carried out to include economic risk considerations.

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Table 1. Results: loss of life estimates and assumed failure probabilities for each scenario.

Flood scenario,	Failure Probability (1/year)	AreaFlooded (km^2)	Exposed population (with 90 % evacuation)	Resulting Fatalities	Overall average Mortality (%)
River, high discharg	1/1000	102	22 120	450	0.02
River, storm surge	1/1000	91	18 160	150	0.008
Lake, West End	1/250	96	16 975	170	0.009
Lake, Bayou St. John	1/250	89	19 980	167	0.008
IHNC	1/500	51	12 662	55	0.004
Multiple Breach	1/5000	102	22 118	280	0.013

Table 2. Metro bowl protection levels required to meet each proposed risk criterion.

Criterion	Probability (1/year)
Individual risk $< 10^{-5}\,\mathrm{yr}^{-1}$	1/4000
Individual risk $< 10^{-6}\,\mathrm{yr}^{-1}$	1/10 000
Vrijling (National)	1/25 000
FN criterion, USACE	< 1/1 000 000
FN 1982 Plot	1/10 000
Economic optimization*	1/1000–1/4000

* Economic optimization based on Jonkman et al. (2009).

Table 3. Preliminary cost estimates abd resulting CSX values for risk reduction measures. Results are for illustration purposes, further investigation of measures, associated costs and risk reduction is recommended.

Measure	Description	Cost, $\$10^6$	Source	Resulting E(n) (fat./year)	% E(n) Reduced	CSX Value ($/fat/yr)
Elevate Homes	5ft (1.52 m) water depth reduction	4000	Estimate	0.5	73 %	2.7×10^9
Increased Protection	1/500 yr level of protection (Hurricane protection only)	2000	Bos (2007)	0.75	62 %	1.5×10^9
Evacuation	95 % of population evacuated	34	USACE (2010)	1	50 %	2×10^7
Relocated population	Persons in “high risk” zone relocated (roughly 50 000 persons)	2000	Hoss (2010)	1.5	26 %	4×10^9

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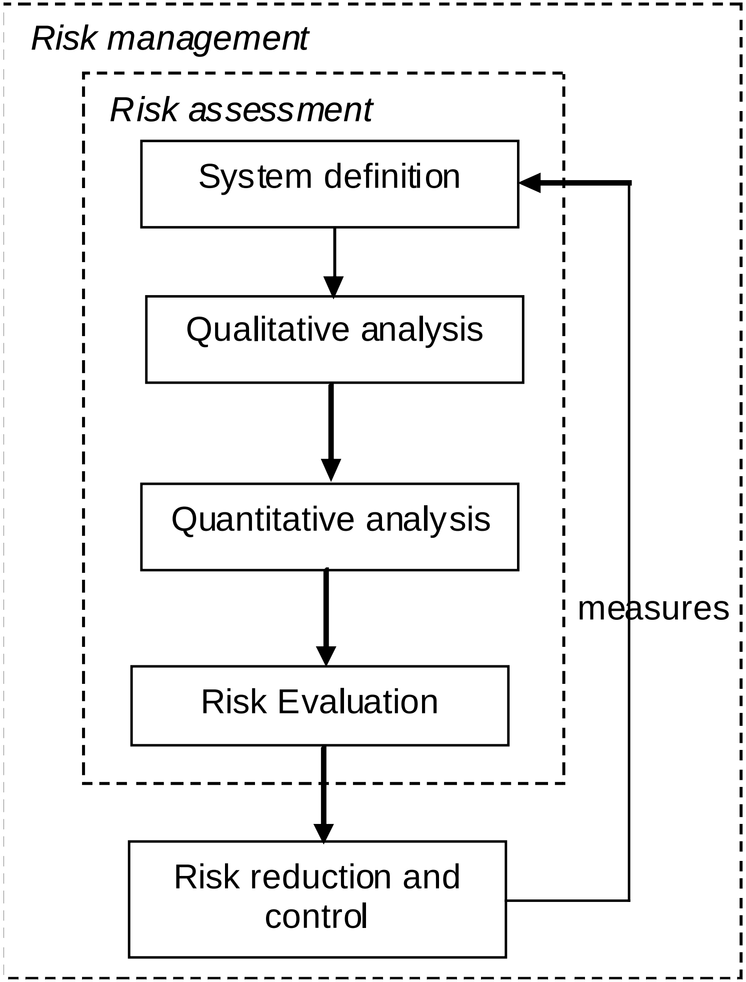

Fig. 1. Steps of a risk assessment (Jonkman, 2007).

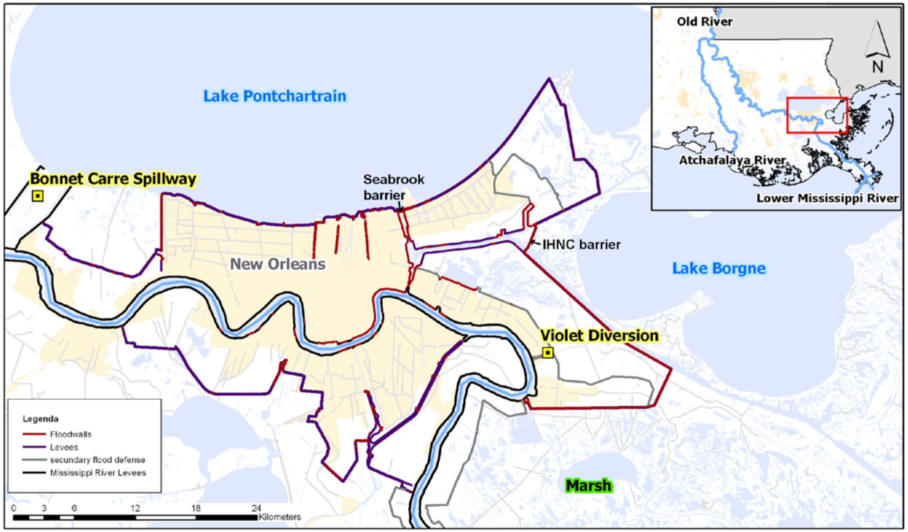

Fig. 2. Upgraded protection for New Orleans and vicinity.

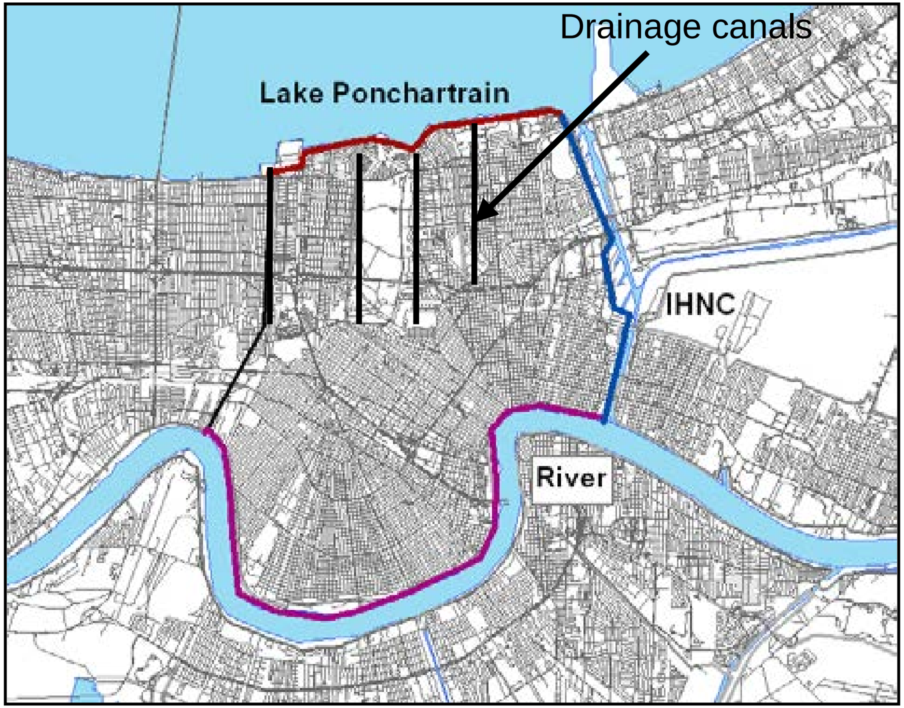

Fig. 3. System boundaries for the New Orleans metro bowl.

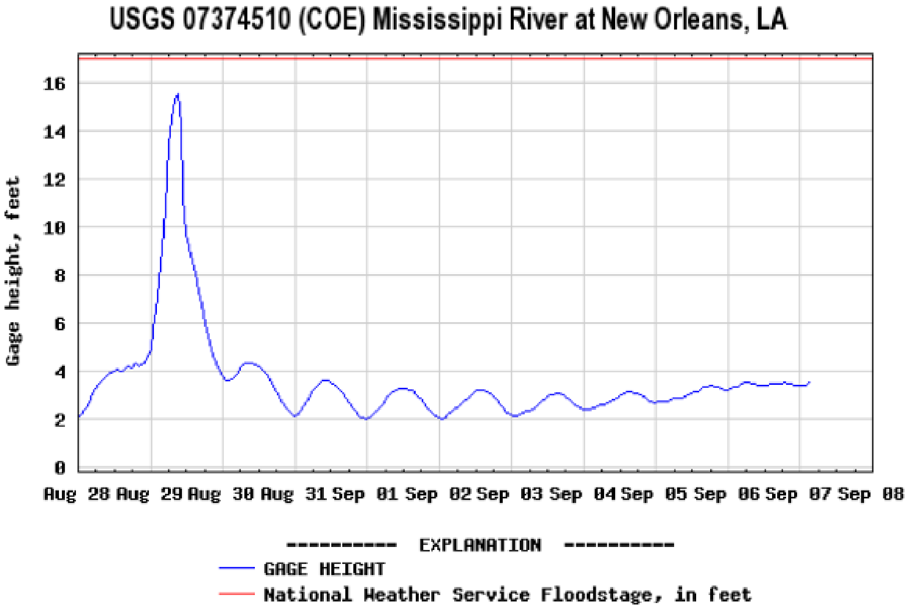

Fig. 4. Stage gage reading at Mississippi River at New Orleans during Hurricane Katrina (Rivergages, 2005).

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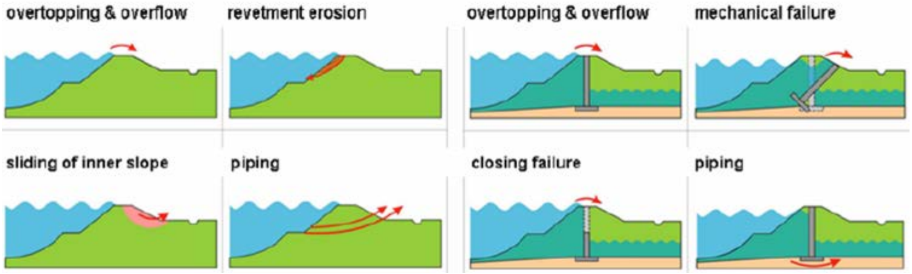

Fig. 5. Failure mechanisms of earthen levees and structural protection measures (Riedstra, 2010).

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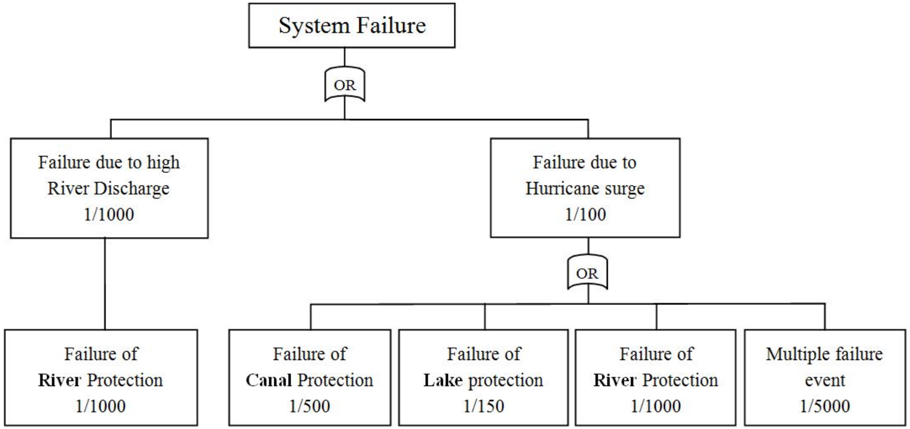

Fig. 6. Fault tree depicting the various ways the system can fail. The probabilities for the various scenarios are indicated as frequencies per year.

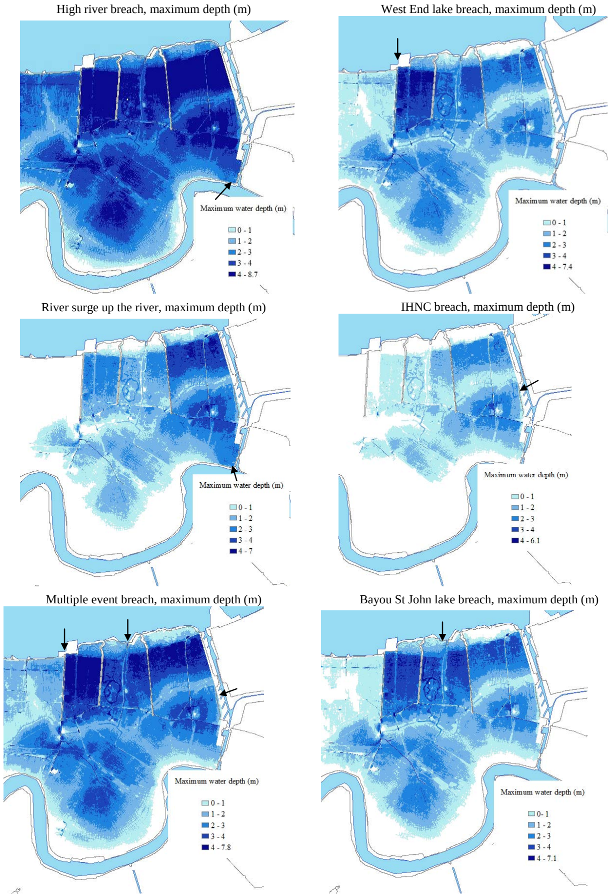

Fig. 7. Maximum water depth for the various breach scenarios for the New Orleans metro bowl. Arrows depict breach location.

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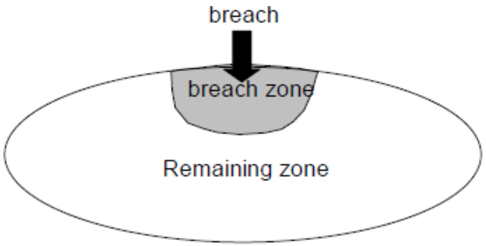

Breach zone: $hv > 5\,\mathrm{m}^2/\mathrm{s}$
⇨ $F_D = 0{,}053$
Remaining zone ($hv < 5\,\mathrm{m}^2/\mathrm{s}$):
⇨ $F_D(h) = \Phi_N((\ln(h) - 5{,}20)/2{,}00)$

Fig. 8. Mortality functions derived from data for New Orleans flooding (Maaskant, 2007; Jonkman et al., 2009).

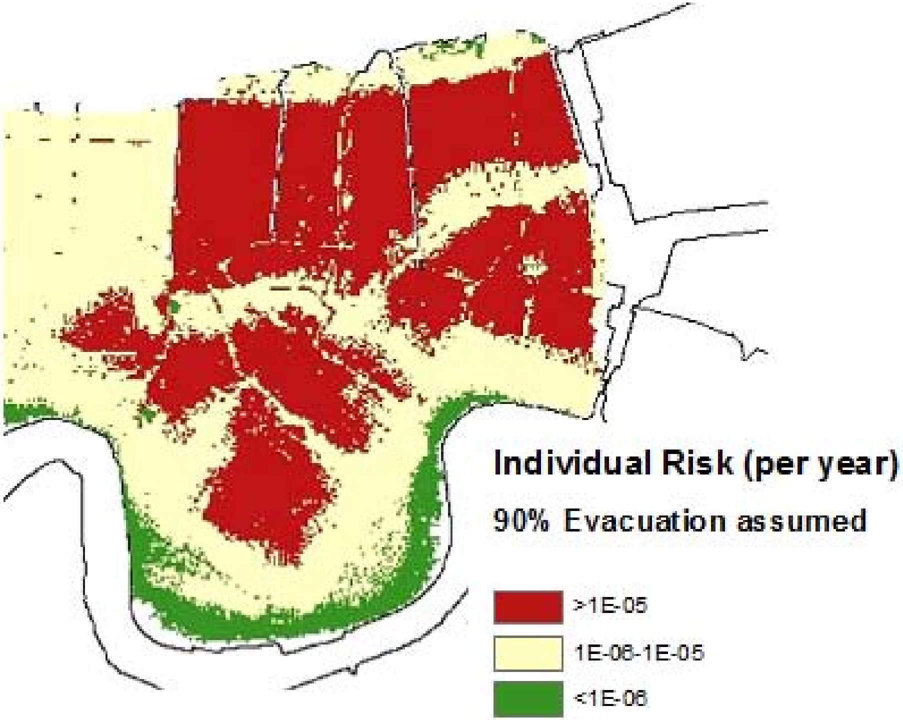

Fig. 9. Map of the individual risk for the metro bowl assuming 90 % evacuation. Values are given as probablity per year.

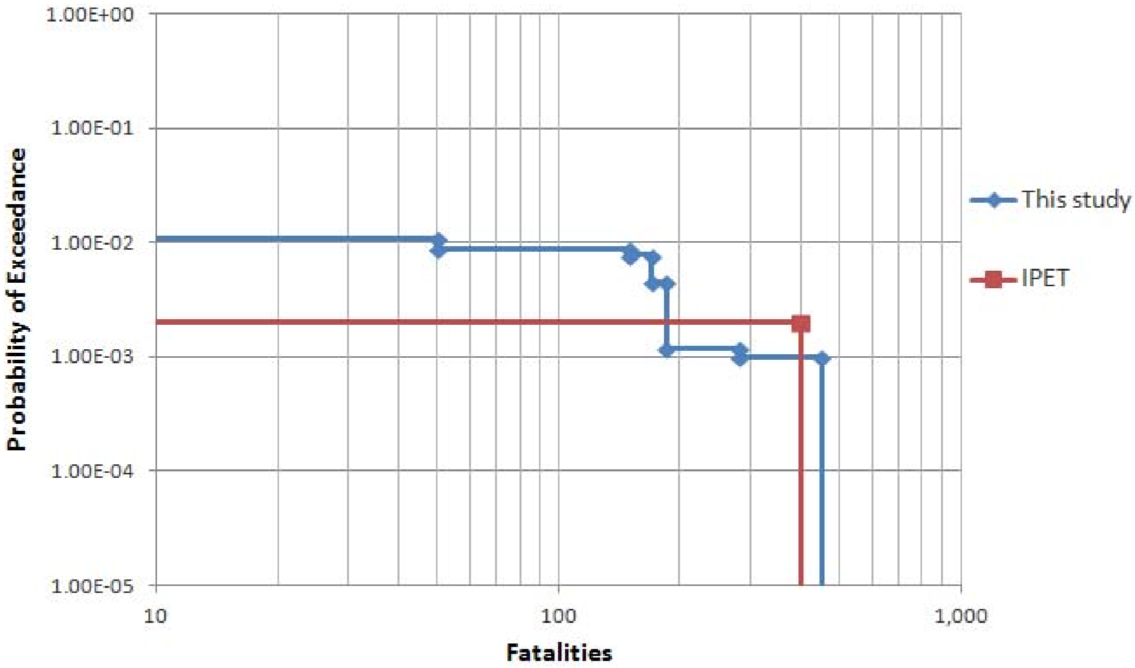

Fig. 10. Results of this study (risk estimate for the metro bowl) and results of IPET (2009) for post-Katrina situation and with 0 % pumping assumed for the 1/500 per year estimate and 100 % pumping assumed for the 1/50 and 1/100 per year estimate.

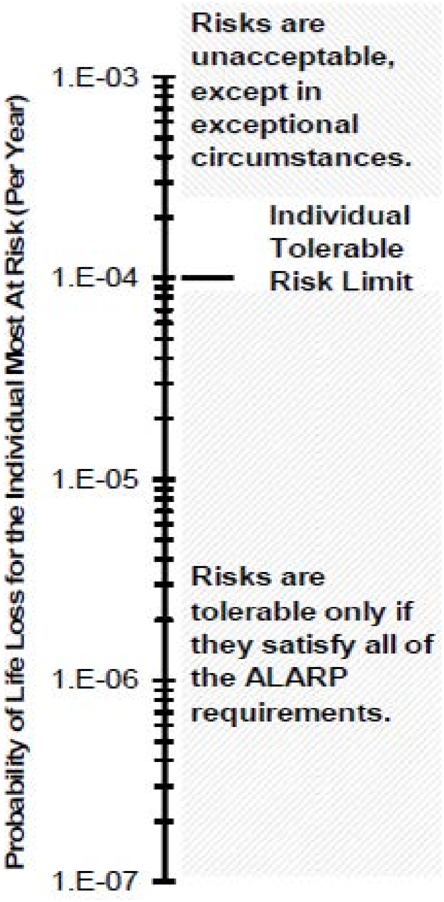

Fig. 11. Proposed individual risk thresholds according to the updated USACE guidelines for Levee safety (USACE, 2010).

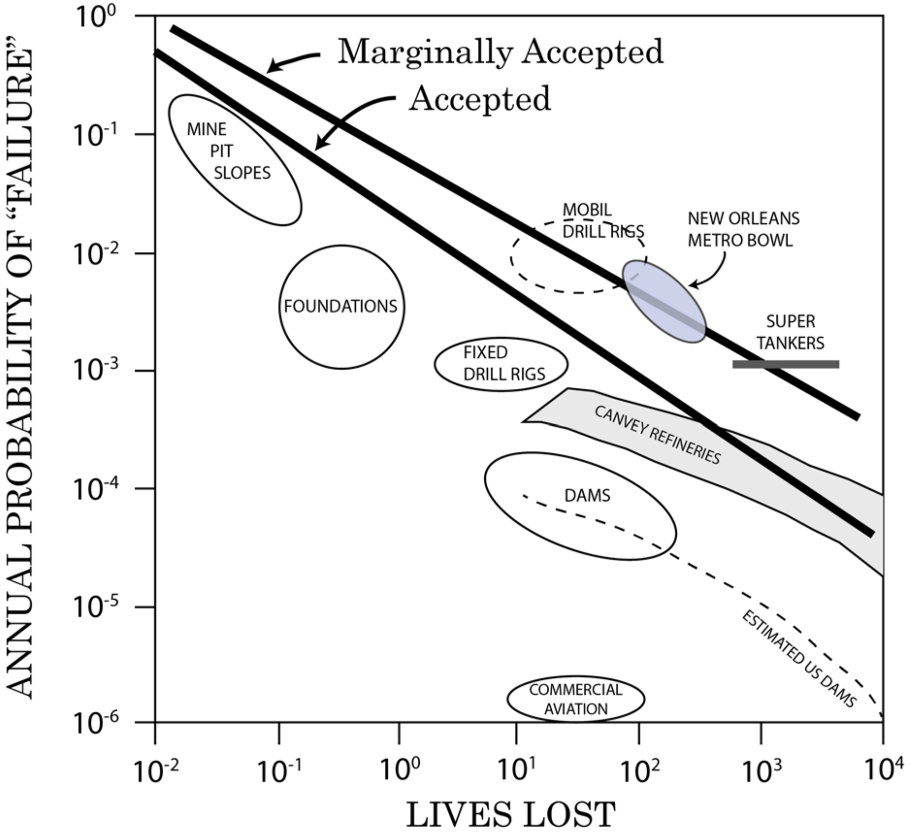

Fig. 12. FN chart of common civil infrastructure risks (Lamberts and associates, 1982).

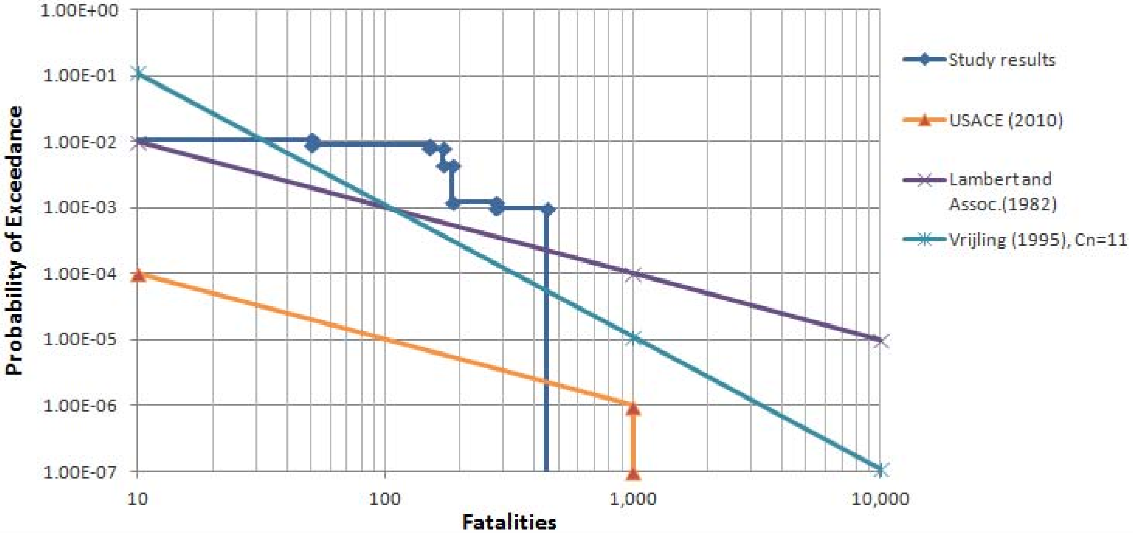

Fig. 13. Societal risk estimate for the New Orleans metro bowl compared to limits proposed in literature.