Journal of
Flood Risk Management

Risk-based design of flood defence systems: a preliminary analysis of the optimal protection level for the New Orleans metropolitan area

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This paper was presented at the 4th International Symposium on Flood Defence, Toronto, Canada (6–8 May 2008), and will be published in a special issue of *Journal of Flood Risk Management* entitled 'Intergrated Flood (Risk) Management' edited by Professor Slobodan P. Simonovic, University of Western Ontario.

DOI:10.1111/j.1753-318X.2009.01036.x

Key words
Flood defence; New Orleans; optimization; risk assessment; safety standards.

Abstract

After the catastrophic flooding of New Orleans due to hurricane Katrina, plans have been developed for the improvement of the flood protection system of the city. In this paper, we apply the principles used in the Netherlands for risk-based design of flood protection systems to the New Orleans metropolitan area. In this so-called economic optimization, the incremental investments in more safety are balanced with the reduction of the risk to find an optimal level of flood protection. Although the analyses are preliminary and not yet fully realistic, the presented outcomes indicate that for densely populated areas, such as the central parts of New Orleans, it could be justified to choose a higher protection level than the currently proposed level of 1/100 per year. The results of the economic optimization can be considered as technical advice that can be used as input for the (political) decision-making.

Introduction

The catastrophic flooding in the United States after hurricane Katrina in late August 2005 illustrated the destructive power of flood events. A large metropolitan area was flooded and more than 1100 people lost their lives in the state of Louisiana. Apart from the human suffering, this event caused enormous economic damage in the states of Louisiana and Mississippi. The preliminary estimate of total direct damages associated with this catastrophe is US$90 billion [US Army Corps of Engineers (USACE), 2006]. Especially the city of New Orleans was severely affected. An estimate of direct property and infrastructure damage due to flooding was published in a report in June 2007 by 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 (such as roads, railroads, water defences, electricity network, drainage, etc.) at US$7 billion.

After this catastrophe the damaged flood protection was first repaired. Congress authorized the USACE to execute the improvements of the flood protection system around New Orleans necessary to withstand a hurricane event with a 1% probability of occurrence every year. The USACE is also investigating the possibility to provide the area for 'category 5 protection'. A category 5 storm is the highest storm level on the Saffir Simpson scale. However, the magnitude of the storm surge is not only related to wind speed, but it is also determined by other characteristics of the storm and local conditions of the area that determine hydraulic conditions, e.g. the local bathymetry. Therefore, it is preferable to define the level of protection of a flood protection system in terms of the return period of hydraulic loads. In the case of a flood defence that is designed for a 100-year return period, it is expected that the design conditions are exceeded, one average, once every 100 years.

The question that remains is 'How safe is safe enough'?[1] The question is how much safety society desires at which

[1] For further academic background regarding this question see for example (Starr, 1969) and (Jongejan, 2008).

costs, and thus how much risk is tolerated. This is of course a political decision. However, information about the consequences of this decision is often desirable, and risk management techniques may be helpful to provide this information. The concept of risk encompasses both the probability of a failure and the consequences of the failure. Risk is generally defined as the product of probability and consequences. The principles of risk analysis are widely used in several engineering fields, for example, in nuclear and chemical engineering. The risk concept can also be used for the design of flood defence systems (see Vrijling, 2001).

Since the major flood of 1953, the Dutch authorities have used risk-based principles in the design, management and maintenance of flood defences (see also 'Economic optimization of flood defence systems in the Netherlands'). In this paper, we apply the principles used in the Netherlands for risk-based design of flood protection systems to the New Orleans metropolitan area. After the catastrophic flooding of New Orleans due to hurricane Katrina plans are developed for the improvement of the flood protection system of the city. In this so-called Louisiana Coastal Protection and Restoration (LACPR) project risk will be an important element and a risk-informed decision framework has been developed (LACPR, 2007). This paper demonstrates how optimal safety levels for this area can be derived by means of so-called economic optimization. The results will give insight into the order of magnitude of the protection level that could be chosen based on such an analysis. The analysis focuses on the metropolitan area of New Orleans and is based on simplified yet realistic information. These simplifications are discussed in this paper and at the end of this paper we will describe how a more detailed analysis can be implemented to add a level of rigour, which is both practical and necessary for the improvement of the results.

Background

A Dutch perspective on coastal Louisiana

Parts of the presented study have been developed as part of the so-called Dutch Perspective [Netherlands Water Partnership (NWP), 2007]. This perspective was prepared after hurricane Katrina for coastal Louisiana by Dutch experts in the field of water and flood risk management. The study presents a perspective for long-term flood risk reduction of coastal Louisiana and for strengthening the natural ecosystem functions of the Mississippi Delta, aimed at stabilizing the landscape. As part of the study several alternative strategies were considered. These strategies included an open system, a semi-open system and a closed system. Based on the characteristics and impacts of these strategies the project team formulated a preferred strategy, which consisted of a combination of strengthened levees around the New Orleans metropolitan area and wetland stabilization measures. A visual impression of the strategy is shown in Figure 1. It has to be noted that the preferred strategy can be considered as a first set of ideas and that further elaboration of all the elements from the strategy is needed.

Economic optimization of flood defence systems in the Netherlands

Large parts of the Netherlands are below the sea level or the high water levels in rivers and lakes. Without the protection of dikes, dunes and hydraulic structures (e.g. storm surge barriers) large parts of the country would be flooded regularly. The last disastrous flood occurred in 1953 when a storm surge from the North Sea flooded large parts of the south-west of the country. Apart from immense economic damage, more than 1800 people drowned during this disaster. Until 1953, dikes were constructed to withstand the highest known water level. After the 1953 flood, the Delta Committee was installed to investigate the possibilities for a new approach towards flood defence. The committee proposed to reduce the vulnerability by shortening the coastline and closing off the estuaries. In addition, safety standards for flood defences were proposed. In an econometric analysis the optimal safety level was determined for the largest flood prone area, South Holland (van Dantzig, 1956). In this economic optimization, the incremental investments in more safety are balanced with the reduction of the risk. The investments consist of the costs to strengthen and raise the dikes. In the simple approach it was assumed that flooding could only occur due to overtopping of the flood defences. Thereby each dike height corresponds to a certain probability of flooding (the higher the dikes the smaller the probability of flooding). Dike heightening leads to reductions of the probability of flooding and the expected damage (= probability × damage). By summing the costs and the expected damage or risk, the total costs are obtained as a function of the safety level. A point can be determined where the total costs are minimal, this is the so-called optimum (Figure 2). The approach has been applied after the 1953 storm surge to determine an optimal safety level for the largest flood prone area, South Holland. In recent work (Eijgenraam, 2006), some modifications of the approach have been proposed.

The analysis of the Delta Committee laid the foundations for the new safety approach, in which dikes are dimensioned based on a design water level with a certain probability of exceedance. The current design criteria and the process for safety evaluation of the flood defences are based on these design water levels. This approach to flood protection is laid down in the flood protection act of 1996. The flood prone areas in the Netherlands are divided in the so-called dike

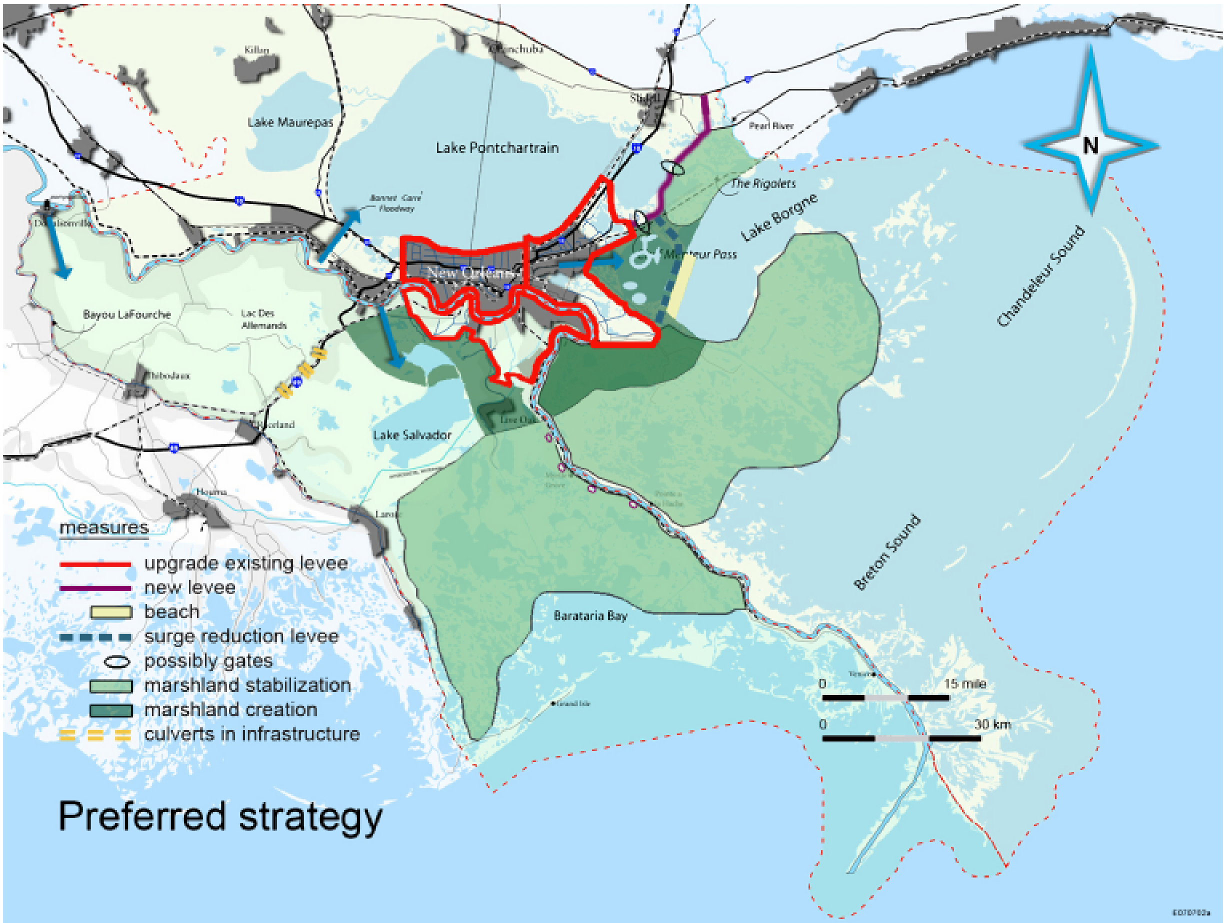

Figure 1 Overview of the preferred strategy from the Dutch perspective report (NWP, 2007).

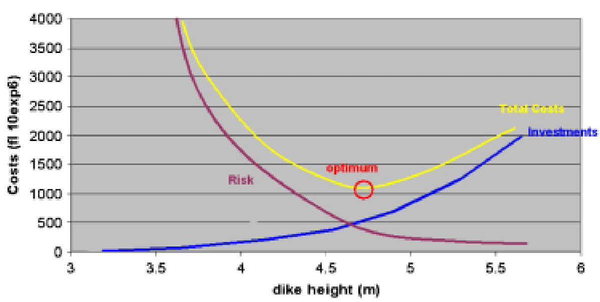

Figure 2 Principle of the economic optimization approach by the Delta Committee.

ring areas, i.e. areas protected against floods by a system of water defences (dikes, dunes, hydraulic structures) and high grounds. The safety standards for the various dikes depend on the (economic) value of the area and the source of flooding (coast or river). For coastal areas design water levels have been chosen with exceedance frequencies of 1/4000 and 1/10 000 per year. For the Dutch river area the safety standards were set at 1/1250 and 1/2000 per year. Some smaller dike ring areas bordering the river Meuse in the south of the country have a safety standard of 1/250 per year.

In the Netherlands, there is discussion whether these standards that were derived mainly in the 1960's do still offer sufficient protection. The economic value of the protected areas and the population has significantly grown since then. Therefore, a new economic optimization of dike rings in the Netherlands is currently being undertaken (Kind, 2008).

The economic optimization has also been applied to other regions. For example, applications to Japan have been explored (Jonkman *et al.*, 2005) and recently calculations have been made for Vietnam (Mai *et al.*, 2008). The benefit of this approach is that, it takes into account the local economic factors (e.g. investment costs, growth rate) and damage level. Therefore the outcomes are relevant in the context of the economic situation in the region that is considered.

Case study area and assumptions

Study area: the New Orleans metropolitan area

The focus area in this study is the New Orleans metropolitan area, see Figure 3. It is bounded by the wetlands in St Charles Parish in the west, Lake Pontchartrain in the north, Lake Borgne in the east and the Mississippi river in the south. The area is threatened by flooding from different sources. Hurricanes, high river discharges and heavy rainfall can all lead to flooding. The focus in this investigation is on the protection against hurricane flooding. In the context of the 'Dutch perspective', a (new) flood protection system has been proposed for the New Orleans metropolitan area. It consists of three so-called dike rings or bowls, two northern dike rings (east bank) and one southern dike ring (on the west bank), see Figure 2. In brief, the works in the two northern dike rings include an upgrade of the existing levees along the Lake Pontchartain (22 miles in the dike ring 1, and 13 miles in dike ring 2) and the eastern side of the city (14 miles). In the eastern alignment 19 miles of new levees will be constructed. Floodgates will be constructed in the Inner Harbour Navigation Channel (IHNC) and in the Mississippi River Gulf Outlet (MRGO) (see NWP, 2007, appendix H for further details).

Approach, assumptions and input information

Approach

We use the economic optimization approach as described in the previous section. To carry out this approach information is needed for the following elements: (1) the damage due to flooding; (2) the safety level for different system configurations expressed by means of a probability of flooding; (3) the investment costs required for improvement of the system as a function of the safety level. Further below, the assumptions and input information for these elements are summarized. In this first order estimate, indicative but realistic estimates for input data for investments costs, flood damage, etc. have been used. The presented data are best (but realistic) estimates based on available sources. The sensitivity of the outcomes (i.e. the optimal level of protection) will be investigated for different values of the above-mentioned parameters.

Damage

For the analysis of damage we focus on the potential damage due to hurricane flooding. The considered bowls can flood in different ways due to different hurricane scenarios. The internal topography and the presence of internal boundaries, such as the ridges, could affect or stop the flood flow.

Table 1 gives an overview of pre- and post-Katrina damage values for the dike rings shown in Figure 2. Before Katrina the total maximum damage in the northern dike rings is estimated at US$57 billion. The maximum damage is determined for a situation where the whole area is flooded up to 35 ft deep. This is not a realistic flood scenario but gives an estimate of the absolute maximum damage. In the post-Katrina situation, taking into account reductions in the

Table 1 Overview of maximum damage values for the different dike rings in 10^6 US dollars (Source: data used by IPET consequence analysis, mean values)

	Pre-Katrina	1-6-2006
Total north 1	44.282	32.128
Total north 2	12.837	1.334
Total north	57.119	33.462
Southern dike ring 3	19.270	19.270

Figure 3 Overview of New Orleans metropolitan area and proposed flood protection systems in de Dutch perspective: (1) northern dike ring 1 (central part of New Orleans); (2) northern dike ring 2 (New Orleans East and St Bernard); (3) southern levee ring (west bank).

population and the economic value, the maximum damage in the same area was estimated at US$33 billion, implying a reduction of more than 40%.

For a full analysis, different flood scenarios for various hurricane intensities and breaching points would have to be defined. Such an approach would require an in depth and detailed assessment that would not be possible within the constraints of this study. Here a simpler approach is chosen and one 'average' damage value is used for each bowl. It represents the average damage for different possible flood scenarios of the dike ring. Because it is an average damage value it is assumed to be independent of the return period of the hurricane.

In assigning a damage value we use the part of the damage that can be related to the performance of the hurricane protection system. This implies that damage due to failure (breaching) and overtopping of levees will be included. The damage due to rainfall has to be excluded from the analysis as this is related to the drainage and pumping systems. Below the average damage values for the three bowls are shown. These have been determined based on the above assumptions and existing studies related to flood damage (Kok *et al.*, 2006; IPET, 2007a). We use the following figures: (1) northern dike ring: central New Orleans: US$15 billion; (2) northern dike ring: New Orleans East: US$10 billion; (3) southern dike ring: US$5 billion. We know that the damage of a flood depends on many factors, like for example the water levels on lake Pontchartrain, the breach location and the cause of flooding (overtopping or breaching). In (Aalberts, 2008) a number of flood scenario's has been analysed, and based on these results a representative damage figure is selected for each bowl. This assumption is discussed in 'Discussion' section of the paper.

In the economic optimization, the present value of the yearly expected damage is calculated. Estimating the development of the expected damage requires the selection of values for several parameters for which the future development is inherently uncertain. A number of pragmatic assumptions has been taken to be able to give insight into the results of the economic optimization.

An infinite horizon is used, in determining the present value, for the following reasons:

- Investments in flood defences have a long-time horizon, at least 50–100 years. In practice it is also shown that this period accounts for the largest part of the net present value.
- The consideration of very long or infinite time horizons raises issues on the intergenerational equity of such long-term investments. However, as argued above the largest part of the discounted costs and benefits can be attributed to the generation that lives in the coming decades.

A real discount rate of 4% is assumed [it follows from the long-term historical interest rate (6%) minus inflation (2%)]. The choice of a long-term discount rate is always critical, and in the literature it is concluded that there is no 'single' discount rate that is appropriate for all budgetary processes (Kohyama, 2006). However, from an economical point of view a choice has to be made about the value of the discount rate.

Next, we assume that the damage will increase, because of economic growth. Neglecting economic growth would lead to an under estimation of the future risk and therefore it is assumed that the yearly increase in damage is 1%. This number is also uncertain, and based on subjective estimates of future expectations.

The flooding probability will increase because of sea level rise. A figure of 1% per year is assumed for this reason. This number has been derived by comparing the expected sea level rise from available climate change scenarios with statistics on the probability of occurrence of extreme water levels. This means that in the calculation of the present value the discount rate is adjusted for economic growth and the yearly probability. Simple mathematics shows that a net discount factor of 2% per year has to be used.

Our approach is based on expected values and assumes that the policy makers and citizens are 'risk neutral', that is that they are indifferent between 'a single large loss at one moment in time' and 'the accumulation to the same loss by many events distributed over time'. A further discussion on possible effects of risk aversion is included in 'Method for optimization and developments in time'.

Safety levels

For the analysis of the safety of different system configurations we use the concept of the design water level. It is assumed that the system is designed to safely (i.e. without failure) withstand water levels below the design water level. Water levels exceeding the design water level will lead to severe overtopping and consequent failure of the flood defence system. For the hydraulic conditions, a probability of exceedance (per year) can be derived. This implies that the probability of failure of the flood defence system is assumed to equal the probability of exceedance of its design water level. It is noted that for a full probabilistic approach the joint probability of both water levels and waves has to be considered in combination with the possibility of breaching of flood defences for different hydraulic conditions. The following assumptions have been used:

- In analysing the safety level we take the pre-Katrina situation as a starting point. We estimate that the pre-Katrina safety level was 1/50 per year.
- The construction works after Katrina can be seen as a first improvement of the system reliability to approximately a level of 1/100 per year. It is thus investigated in this analysis whether further improvement is justified.

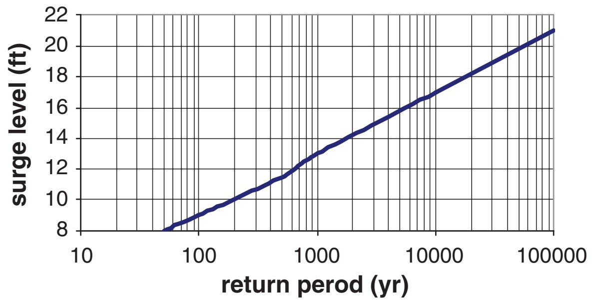

Figure 4 Relationship between return period and surge level for Lake Pontchartrain (*source*: data from IPET).

- We investigate the order of magnitude of the optimal protection level by considering various predefined safety levels: 1/100, 1/500, 1/1000, 1/5000, 1/10 000, 1/100 000 per year.
- The relationship between return period and storm surge level is based on results of IPET, see Figure 4 for an example for Lake Pontchartrain. From such figures the increase in the surge level can be estimated that corresponds to a change in the return period by a factor 10. For example, from Figure 4 it can be seen that a change in the return period from 100 to 1000 years corresponds to an increase of the surge level by 3–4 ft (1–1.2 m). Based on the available data, we assume a linear relationship between the natural logarithm of the return period and the surge level for return periods larger than 100 years. Similar figures have been used to calculate the increase in water levels for other areas, such as Lake Borgne.
- It is assumed that breaching of the flood defence system will occur if the design water level is exceeded. It is possible that other failure mechanisms, such as instability or piping, can lead to failure for water levels below the design level. However, following the design approach that is used in the post-Katrina situation, it is assumed that the flood defences are constructed in such a way that failure below the design water levels is very unlikely. In addition possible resilience of the system and events that are associated with only overtopping are not considered in the quantitative analysis. These are important simplifying assumptions. However, these assumptions seem reasonable, because it is a matter of a good design that failure of the flood defences below design water levels is unlikely. A more extensive discussion of these factors and their influence on the results is presented in 'Failure mechanisms and design water levels'.

Investment costs in the flood defence system

We analyse the required investments in the flood defence system. It is investigated how much investments are required to make a safe system for water levels below the design (water) level. The physical measures in the base case consider dike strengthening and the creation of storm surge barriers. The effects of other measures (e.g. damage reduction and wetlands) can be considered in the same conceptual manner. In the base case optimization these effects are not treated here in detail.

- The investments costs include the costs of additional costs of management and maintenance.
- The investment costs made in the context of Taskforce Hope have been included in the cost estimates.
- The cost estimates have been made based on the length of the levees that have to be upgraded or constructed and unit prices per kilometer of levee strengthening or construction, see appendix G of the Dutch perspective report (NWP, 2007).
- The costs of floodgates in the IHNC and MRGO have been assumed as fixed costs. It is thereby assumed that they are constructed in such a robust way that they are functioning well for different safety levels.
- Overall, the cost estimates are first order and indicative. For a realistic calculation of investment costs, more detailed designs have to be used. To account for variations and deviations in the cost estimates the investment costs have been included in the sensitivity analysis.

Results

Results for central part of New Orleans

The current yearly risk of this dike ring is equal to US$300 million (= $15 billion × 1/50). This value can be converted to a present value by dividing by the 'net' discount rate (0.02), leading to a present value of US$15 billion. If the safety level is improved to 1/100 per year, the present value of the yearly risk will decrease by US$7.5 billion, and if the safety level is lowered to 1/1000 per year, the present value of the risk will decrease by US$14 billion. This decrease in present value can be considered as the benefits of the project. The results show that the choice of a protection level higher than 1/100 per year, such as 1/500 or 1/1000 per year would already lead to a very significant reduction of the risk level. However, in a cost–benefit analysis also the cost of the improvements in safety is important. The results for the base case are presented in Table 2 and Figure 5. The optimal level of flood protection that follows from the analysis is 1/5000 years (indicated in bold in the table). Figure 5 shows the following. In terms of total costs there is not much difference between a 1/1000 and 1/100 000 per year protection level. The additional investment costs to reach a 1/10 000 per year level of protection (US$200 million) or a 100 000 per year level (US$700 million) are relatively limited. For protection levels of 1/100 000 per year and

Table 2 Economic optimization for Northern dike ring, central part of Orleans: Input information and results

Return period (yr)	100	500	1000	**5000**	10 000	100 000	10 00 000
Design surge level Lake Pontchartrain (ft)	9	11	13	**15**	17	21	25
Investments ($)	2.2E+09	2.4E+09	2.6E+09	2.9E+09	3.1E+09	3.6E+09	4.1E+09

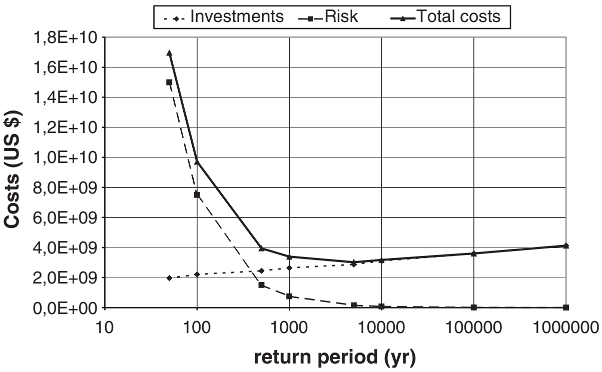

Figure 5 Results of economic optimization for the northern dike ring, central part of New Orleans.

higher the contribution of the risk costs to the total costs becomes negligible.

The results for the other two bowls (New Orleans East, southern bowl) are shown in Figure 6. For both the areas the optimal level of protection that is found corresponds to a return period of 1/1000 per year.

Sensitivity analyses

As the estimates that have been used in this study are first order and rough estimates, a sensitivity analysis has been carried out. The sensitivity of the outcomes of the calculated optimal safety level has been investigated for variations in the following parameters: the flood damage value, the value of the real discount rate and the investment costs. Table 3 summarizes the results for the central part of New Orleans. This outcome is not very sensitive to changes in damage level and the investment costs. Only when lower damages are assumed the optimum level of protection reduces to 1/1000 per year.

Discussion

In this section a number of relevant issues and assumptions related to the assessment of the risk will be discussed. In this paper the assumptions made in the previous analyses are discussed, and the impact of each assumption will be explained. We also present possible improvements to come to a more accurate analysis of these aspects in order to achieve a better estimate of the risk level.

Failure mechanisms and design water levels

In the presented analysis, it has been assumed that the levee system catastrophically fails if the design water level is exceeded. It is thereby assumed that the system is designed in such a way that the contribution of failure mechanisms other than overtopping to the system failure probability is negligible as this is also one of the design principles that is adopted in the reconstruction of the levee system after hurricane Katrina.

However, failure mechanisms other than overtopping could still be relevant for the failure analysis especially for events with small probabilities. During Katrina for example, flood defences have failed due to other causes, such as geotechnical failure mechanisms such as instability. Therefore, the analysis of the contribution of these mechanisms to failure is strongly recommended with the approaches developed in the IPET ‘risk analysis’ project (IPET, 2008). The impact of including other mechanisms in the analysis is limited if the reconstructed water defences are build in such a way that the probability of failure is very low if the water levels are below the design water level.

One other aspect that has not been considered is the resilience of the system, i.e. its capacity to withstand loads higher than the design water levels (Ogunyoye *et al.*, 2008). In this context it is also desirable to analyse flood scenarios that are associated with overtopping of the levee system and not breaching (see next section).

For the analysis of measures and investment costs so-called design water levels have been used. Results have been from the IPET study and these are available for return periods below 1000 years. For higher return periods (10 000 years and further) design water levels can be considered as rather uncertain. In addition, physical limits to hurricane characteristics (pressure, wind speeds) and hydraulic effects (surge and waves) could affect the design conditions for higher return periods. Therefore, the hydraulic boundary conditions for higher return periods have to be examined further.

Flood scenarios and damage

In the presented analysis, an average damage has been assumed (see ‘Approach, assumptions and input information’). For a full analysis different flood scenarios for various hurricane intensities and breaching and overtopping locations would have to be defined. For example, the damage for

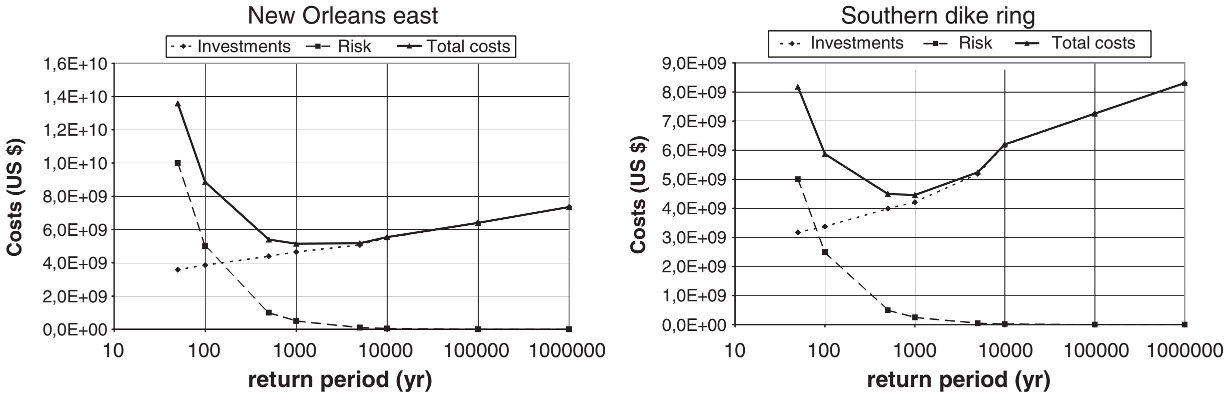

Figure 6 Results of economic optimization for the New Orleans East and the southern dike ring.

Table 3 Results of sensitivity analysis for the New Orleans metro bowl

		Flood damage		Net discount rate		Investment costs	
	Base Case	50% lower	100% higher	50% lower	100% higher	50% lower	100% higher
Optimal Safety level	1/5000	1/1000	1/5000	1/5000	1/5000	1/5000	1/5000

the flooding of New Orleans East would be smaller than the damage for the central part of Orleans. In a risk analysis different flood scenarios can be elaborated and their probabilities and consequences can be estimated. For assessment of the consequences, two dimensional hydraulic simulation models can be used to analyse the flood characteristics of a scenario as input for damage modelling. An example of the results of a flood simulation for the flooding of the St Bernard area of New Orleans during Katrina is shown in Figure 7.

In this context it is also particularly important to develop flood scenarios, flood maps and consequence assessments for flood events that are associated with overtopping (without breaching) of the levees. These events will lead to more limited flooding and damage than breaching events. As overtopping is especially relevant for events with relatively low return periods this type of event will likely affect the expected damage. In the analysis presented in this paper overtopping events have been neglected and this might contribute to an under estimation of the risk. On the other hand, full breaching and flooding has been assumed if the water level exceeds the design conditions and this is a somewhat conservative assumption as the system could still have some resilience. Both the return periods and resulting damages of overtopping events can be included in a more detailed optimization to get a more accurate insight into the level of flood risk.

The impact of our assumption of using only one damage number can be substantial, and the impact depends on the deviation of the actual expected value of the distribution of damages from our assumption of one damage value. This can only be clarified by a further investigation of the damages for the different possible scenarios.

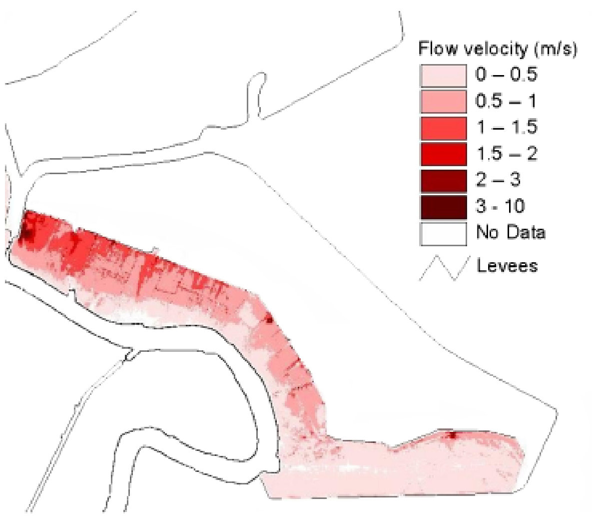

Figure 7 Flow velocities for Lower Ninth Ward from a flood simulation for the breaches observed during hurricane Katrina (Jonkman, 2007).

Measures and the effects of wetlands

In the analyses of measures in the previous sections mainly the effects of levees and storm surge barriers have been included. However, other measures in a multiple lines of defence strategy could reduce the risk as well. Examples of such measures include: wetlands, compartment dikes within one dike ring and evacuation.

One specific measure that receives much attention is the (re)creation of wetlands and barrier islands. Their presence could reduce the surge levels near populated areas (see Grzegorzewski *et al*., 2008). The impacts of wetlands on the surge levels used for design can be taken into account. In the presented study, conservative assumptions have been made in the determination of design water levels with respect to the effects of wetlands/marshes as the development of the wetlands over the coming decades is not certain. Thereby the design water levels that were used in this study could be somewhat conservative for the present situation. Further insight into the effects of wetlands on the storm surge levels could be obtained by additional hydrodynamic storm surge simulations, with and without wetlands (Loder *et al*., 2009).

The impacts of wetlands could also be taken into account in a cost–benefit approach by estimating the potential risk reduction and the investment costs for wetland restoration. In the decision-making also the ecological and economic values and benefits of wetlands should be assessed. It is noted that the restoration of wetlands is a relatively slow process. It will likely take decades to stop the process of deterioration of the wetlands, and even more time to increase the quality of these wetlands. The time needed to restore the wetlands is an important issue from a risk management perspective and it is therefore likely that wetland restoration cannot replace the defence with hurricane protection but could be of additional value.

Overall, a further analysis of the impact of wetlands on surge levels and the associated costs would be needed to make more thorough statements regarding their effectiveness. Relevant issues are the effects of wetlands under extreme hurricane conditions and the fact that the reduction of surge levels is dependent on the hurricane track and the duration of the hurricane.

Method for optimization and developments in time

In the elaborations in this report the method for economic optimization proposed by van Dantzig (1956) has been used. Recently an improvement of this approach has been proposed by Eijgenraam (2006). In essence, the difference is that van Dantzig assumes one major improvement at the current moment, while Eijgenraam considers the periodical character of the improvement of the flood defence system under changing conditions such as economic growth, sea level rise, etc. Application of the approach of Eijgenraam (2006) to the New Orleans area leads to similar results (NWP, 2007, appendix E).

The applied method for economic optimization is based on expected damages and is thereby considered as a risk neutral approach. A single large loss has the same expected damage as multiple smaller losses that accumulate to the same expected damage. It is possible to take into account risk aversion to larger damages into account in the economic optimization (Slijkhuis *et al*., 1997) and this results in a higher level of the optimum. However, the economic optimization is based on a risk neutral cost–benefit analysis. It is therefore suggested to involve the societal aversion against larger accidents with many fatalities in the development of criteria for evaluating the risks to people (see also 'Loss of life and risk criteria').

The flood defence scheme considered in the project is mainly developed at a conceptual level. The investment costs have been estimated based on rough indicators. There is thus considerable uncertainty associated with these estimates. Although anticipated developments have been taken into account in the proposed design, several developments could affect the outcomes of the economic optimization:

- Loss of marshes, sea level rise, increased hurricane activity could lead to increase of loads.
- Subsidence of the soil or new insights in behaviour of designed flood defence works could affect the resistance of the system.
- Changes in construction techniques, market prices, etc. could lead to differences investment costs.
- Changes in population, economic activity and spatial development could lead to changes in damage.

Assumptions have been made with respect to these developments in the current proposed analyses (see 'Case study area and assumptions'). However, given the uncertainty in such future developments it is recommended to develop a management and maintenance system, (see also NWP, 2007, appendix K). By means of a management system it could be investigated whether the system that is in place still complies with the initially intended design criteria. If the performance of the system has weakened over time, e.g. due to subsidence, corrective action could be taken to improve the performance, see Figure 8.

In the context of the risk assessment it could be desired that the strength and protection level system increases over time when the consequences of failure increases (e.g. due to economic or population growth). Figure 8 also explains why additional strength (on top of the minimal requirements) could be given to a new system that is constructed. In that case some degradation can be accepted before corrective action is needed. It can be shown that this is attractive from an economical point of view (Eijgenraam, 2006).

Application to other areas

The economic optimization has been applied to dike rings around densely populated areas with high (economic) values. This resulted in high levels of protection in the order

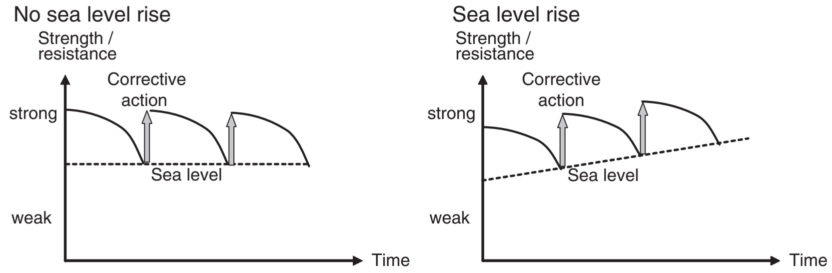

Figure 8 Development of the resistance of a system over time and the effects of periodical corrective action for situation without sea level rise (left) and with sea level rise (right – linear sea level rise assumed).

of magnitude of 1/1000–1/5000 per year. The dike ring concept can also be used for other populated areas in south-east Louisiana. For example for the Plaquemines, it could be investigated if local communities could be protected by a dike ring. For these cases it is expected that the economic optimization will lead to lower levels of protection, because the required investment costs will be relatively high, while the protected value is relatively limited. For some cases it could even turn out that investment in a dike ring system is not justified from a cost–benefit point of view. In these cases other strategies could be investigated to offer a certain minimum level of protection for these areas, e.g. raising of homes, mounds, evacuation plans, etc.

Loss of life and risk criteria

The current analysis is mainly based on the analysis of economic damage. One other important aspect for decision-making is the number of fatalities caused by a flood. Hurricane Katrina caused more than 1100 fatalities in the state of Louisiana. Future flood scenarios of New Orleans might lead to loss of life. An estimate of the loss of life can be given based on: (1) information regarding the flood characteristics, (2) an analysis of the exposed population and evacuation and (3) an estimate of the mortality among the exposed population. This shows that several measures could reduce the loss of life, such as evacuation or the limitation of the flooded area. Methods have been developed for the estimation of loss of life for flooding of low-lying areas (IPET, 2007a; Jonkman, 2007). Separate risk criteria could be developed (e.g. risk limits in a so-called FN curve) to set acceptable risk levels in terms of fatalities and acceptable flooding probability (Vrijling *et al.*, 1998; Jonkman *et al.*, 2008). An example of such a criterion that is used for the risk assessment of large dams by the US Bureau of reclamation is shown in Figure 9. At this moment, similar criteria are not yet available for coastal or riverine flood protection systems. Given the large population in flood prone areas of New Orleans and the observed loss of life due to Katrina, it is expected that the risk to life could still be substantial in this area and will be an important aspect in the discussion on appropriate safety standards.

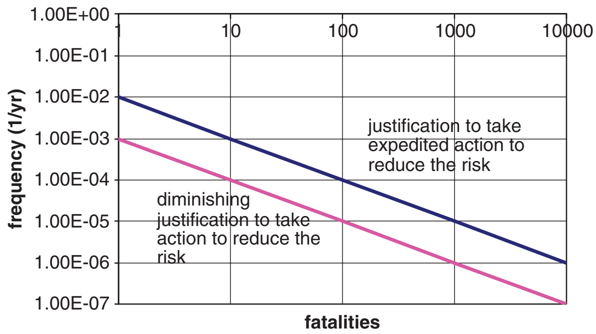

Figure 9 United States Bureau of Reclamation's criteria for large dams (USBR, 2003).

It is also noted that the application of FN curves for risk evaluation and decision-making is criticized by some authors, see e.g. (Evans and Verlander, 1997), as FN criteria do not always result in rational and consistent decisions. Nevertheless, the loss of life is an important aspect of the total consequences of flooding and it is valuable to present this type of risk as input for decision-making. Further discussion and research is necessary to develop standards to limit the risks to people for large-scale flood protection systems.

Concluding remarks

Conclusions

In this paper, we presented the results of a preliminary economic optimization for the safety level of New Orleans. We have used indicative, but realistic estimates for input data. The following has been found:

- Although preliminary and not yet fully realistic the presented outcomes indicate that it is possible to determine the optimal level of safety for the different protected areas in South-East Louisiana.

- The results indicate that for densely populated areas, such as the central part of New Orleans it could be justified to choose a higher protection level than the current level of 1/100 per year. Although the investment costs will be high (billions of dollars), a very large damage can be prevented and a large risk reduction can be achieved. The investments are expected to be cost-effective.
- The optimal protection level for the central part of New Orleans is estimated to be in the order of magnitude of 1/5000 per year. This outcome is not very sensitive for changes in damage level and investment costs. The optimal level of protection for New Orleans East dike ring and the southern dike ring are 1/1000 per year. The following has to be noted: comparison with more recent cost estimates shows that the cost estimates used in this paper are likely somewhat underestimated. Taking into account more realistic (and higher) cost estimates could lead to somewhat lower optimal protection levels. Nevertheless, based on these results and sensitivity analyses it is expected that safety levels that are higher than the 100-year level of protection are always defendable. For example, for the New Orleans metro bowl, the choice of a protection level in the range of 500–1000-year level of protection would already lead to a very significant reduction of the risk.
- The outcomes also show that a differentiation in protection levels between areas could be justified based on the economic optimization. Such a differentiation in protection levels between areas also exists for dike rings in the Netherlands.

Recommendations

This paper included a highly simplified risk analysis and optimization to illustrate the potential application to New Orleans. A more detailed assessment would involve at least the following steps. Firstly, the hydraulic load conditions would have to be determined for a spectrum of hurricanes with different characteristics (pressure, track, etc.) covering different return periods. By using the resulting distribution of hydraulic loads, and the characteristics of the flood defence system, the reliability of the flood defence system can be characterized. Different failure mechanisms and the resilience of the system would be taken into account. As a next step several flood scenarios would be defined, covering both breaching and overtopping events at different locations and for a variety of hydraulic load conditions. These flood scenarios should represent the range of possible flood events and their probabilities could be estimated from the reliability analysis. By means of flood simulations insight would be gained in the effects of the flood scenarios in the area in terms of flood characteristics, such as water depth, flow velocity, arrival time, etc. This information would then be used as input for the economic damage estimation. By taking into account the size of the population exposed and the evacuation and shelter rates the loss of life could also be estimated. The consequence estimates for different scenarios have to be integrated with the probability estimates of the scenarios in order to estimate the level of risk, in terms of economic risk or risk to life. As part of the optimization, several measures and strategies would be defined that could reduce the risk. Also strategies could be analysed that cover a combination of measures, for example, a multiple lines of defence strategy, which consists of combination of wetland restoration, levee improvement and spatial measures in the flood prone area. The effects of measures and strategies on the risk level can be estimated by rerunning the risk model with the proposed measures as input. The effects of alternative levee system configurations (including storm surge barriers) and the effects of wetlands and multiple line of defence systems could be analysed. By analysing different strategies and designs for different levels of safety for their risk reduction and costs insight would be gained in the optimal strategy and the optimal level of protection. Although parts of this approach have been implemented in the risk and reliability analysis (IPET, 2008) further elaboration of the approach is necessary to come to a complete risk characterization and optimization.

In a more complete optimization also the effects of river flooding from the Mississippi river and rainfall could be taken into account. Although these phenomena are independent from hurricane flooding, they might contribute to the overall flood risk level. In that case also expenditures for the reduction of the risk due to river and rainfall flooding have to be considered.

Finally, the results of the economic optimization can be considered as a technical advice to the decision makers. The decision regarding an acceptable safety level is a political choice, which includes more aspects than economics. A discussion on safety levels and the corresponding decision criteria with involvement of the relevant decision makers and stakeholders could support this broader decision process.

Epilogue: hurricane Gustav

Nearly 3 years after Katrina hurricane Gustav illustrated the potential danger of hurricane induced flooding in the New Orleans metropolitan area during early September 2008. This storm made landfall at the Louisiana coast as a category 2 storm. No exact derivations of the return period of Gustav are available, but it is estimated that a hurricane of this size occurs approximately every 20 years in this region.[2]

[2]Data from National Hurricane Center. Available at http://www.nhc.noaa.gov/HAW2/english/basics/return.shtml (accessed 1 November 2008).

Although this number cannot be directly transferred into a return period for hydraulic conditions it is expected the hydraulic conditions (water level, waves) could be characterized by a relatively low return period. Yet, some sections of the New Orleans flood protection system suffered severe wave overtopping (with the still water level close to the top of the walls as could be observed from information in the media), especially along the Industrial Canal. This event illustrates the importance of the discussion on the level of flood protection that the New Orleans metropolitan area should have.

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