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Future risk of flooding: an analysis of changes in potential loss of life in South Holland (The Netherlands)

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ABSTRACT

Potential loss of life is considered an important indicator of flood risk. We examine the future development of potential loss of life due to flooding for a major flood prone area in The Netherlands. The analysis is based on projections and spatial distribution of population under a high economic growth scenario and a loss of life model. Results show that the projected population growth in flood prone areas is higher than average in the Netherlands between 2000 and 2040. Due to this effect the potential number of fatalities is projected to increase by 68% on average for 10 different flood scenarios, not including impacts from climate change and sea level rise. Just sea level rise of 0.30 m leads to an average 20% increase in the number of fatalities. The combined impact of sea level rise and population growth leads to an estimated doubling in the potential number of fatalities. Taking into account increasing probability of flooding due to sea level rise and extreme river discharges, the expected number of fatalities could quadruple by 2040. The presented results give a conservative and upper bound estimate of the increase of the risk level when no preventive measures are undertaken. It is found that the consideration of the exact spatial distribution of population growth is essential for arriving at reliable estimates of future risk of flooding.

1. Introduction

Population and economic growth have historically been higher in populated coastal urban areas around the world. Coastal areas are exposed to many natural hazards such as storms and floods, and their development explains why the number and impacts of natural disasters have taken off rapidly in recent decades. Munich Re (2007) for instance has estimated a four-fold increase in the global number of great catastrophes since the 1970s. Economic losses from natural disasters have in general increased more rapidly than average national economic growth, which points to the possibility that the exposure to natural disasters has increased disproportionally in heavily urbanised coastal areas (Bouwer et al., 2007). It is important to study the factors that may influence the impact of natural disasters in the near future, at scales of 10–50 years, as this particular period allows policy decisions that affect medium and long-term outcomes. In particular the planning and execution of programmes for spatial planning and the prevention of storms and floods in urban areas, for instance, typically take 20–30 years to complete. Conveniently, much information is available for this timescale on projected population, economy, climate, etc. There is also increasing attention for environmental changes that affect development in the near future (e.g. Klijn et al., 2007; MNP, 2007; Aerts et al., 2008).

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Flood risks pose a common threat to many low-lying and heavily populated coastal urban areas around the world, ranging from European coasts, to Chinese and Indian mega-cities, and coastal United States. An assessment of changes in flood risk over time can inform decision makers how changes in exposure could possibly affect safety in coastal urban communities. It could also provide guidance for decision-making regarding risk reduction measures. In addition to the population growth and accumulation of assets, the effects of climate change can lead to an increase in flood risks (IPCC, 2007). If no preventive or risk reduction measures are taken, the probability of flooding can increase due to higher river discharges and storm surge levels at sea. The effects of climate change can both affect the probability of flooding (because higher water levels exceed the design conditions of flood defences) and also lead to an increase of consequences if flooding occurs (higher water levels result in higher damage levels). It is therefore expected that climate change and ongoing development of low-lying areas can affect the risks in flood prone areas, for example in The Netherlands.

Risk is made up of the probability of a hazard, the exposure to that hazard, and vulnerability, which is the extent to which a system or population is susceptible to, or unable to cope with the impacts. Exposure here is the number of people and assets that are at risk. In view of the changing societal and environmental consequences of disasters, the development of exposure can be studied by means of quantitative indicators of societal and environmental changes. Various studies have highlighted the economic losses from natural disasters as an important indicator of changing exposure; see for instance Pielke et al. (2008). Relatively few studies however have addressed the impacts of socio-economic development and climate change on potential fatalities from natural disasters. The probability of loss of life is an important indicator for environmental risk assessment and decision making in The Netherlands (RIVM, 2003). The number of fatalities from natural disasters around the world apparently has been declining over recent decades, which may be an indication that forecasting, early warning and evacuation have been successful at reducing the loss of life (IFRC, 2002; Goklani, 2006). As The Netherlands is densely populated and situated in a flood prone area, the increasing exposure due to growing habitation and accumulation of values in low-lying areas will be particularly relevant for this country. Some studies have argued that current measures for flood prevention and risk reduction under the socio-economic developments over the past decades The Netherlands have been insufficient to maintain reasonably low risk levels (Bouwer and Vellinga, 2007; Ten Brinke et al., 2008).

In this article we focus on the projected flood risks to people for the area of South Holland. This is the flood prone area in The Netherlands that has the highest number of inhabitants and contains the economic and political heart of the country. It has approximately 3.6 million inhabitants and includes many of the largest cities such as Amsterdam, Rotterdam and The Hague. The objective of the analysis is to investigate the temporal development of flood risks, in particular the potential loss of life. With the use of available flood simulations we have made an estimate of the potential loss of life in the year 2040 and compare this to estimates for the year 2000. In the future scenario we take into account the effects of socio-economic developments, in particular projected new residential areas, and the possible impacts of climate change and consequent sea level rise and river flood probabilities.

Related research questions that will be treated are:

- What is the effect of population growth on the potential number of fatalities due to flooding from river and coast?
- In what way does the location of the projected new residential areas affect the potential number of fatalities?
- What is the effect of increased flood depths due to sea level rise on the potential number of fatalities?
- What is the combined effect of sea level rise and population growth on the potential number of fatalities?
- How will the probability of loss of life change with climate change?

2. Methods

In the estimation of changes in the potential loss of life and risk levels we use the following conceptual approach. The potential number of fatalities (N) for a flood event is determined by the components event mortality (F_d) and exposed population (N_{exp}) (Jonkman, 2007):

$$N = F_d N_{exp} \tag{1}$$

By definition, the event mortality (F_d) is the number of fatalities (N) divided by the exposed population (N_{exp}). Both mortality and exposed population can change over time and thus affect the number of fatalities due to flooding. For example, mortality (F_d) can change because a population becomes more vulnerable to flooding, for instance due to changes in building quality and age distribution of the population. However, the number of exposed people (N_{exp}) can also change due to changes in the size and spatial distribution of the population.

An estimate of potential loss of life due to a flood event for South Holland can be given based on (1) information regarding flood characteristics; (2) an analysis of the exposed population, evacuation and shelter; and (3) an estimate of the mortality amongst the exposed population. The mortality is estimated with a so-called mortality function, which relates the mortality amongst the exposed population to the flood characteristics (Jonkman, 2007). The mortality function that is used in this article relates the mortality to the flood depth. This method has been proven to be very useful in estimating potential loss of life. However, it is important to note that socio-economic factors also determine vulnerability to flooding. Social vulnerability for instance, including poverty and household income, has shown to be significantly related to the number of flood casualties (Zahran et al., 2008). In previous studies mortality functions have been derived for inundation of low-lying areas due to failure of flood defences in The Netherlands (Jonkman, 2007; Jonkman et al., 2008a). In this article the most recent mortality function available has been used, which is based on data from the New Orleans flood, following the landfall of hurricane Katrina in August 2005 (Boyd, 2006; Jonkman, 2007; Maaskant, 2007; Maaskant and

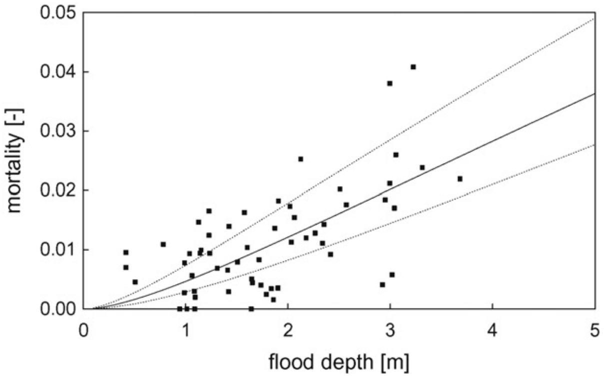

Fig. 1 – Mortality function and 5–95% uncertainty bounds (based on mortality data for the flooding of New Orleans, USA, after hurricane Katrina in the year 2005).

Jonkman, 2007). The tragic Katrina event that led to more than 1100 fatalities in the state of Louisiana, gave new information regarding loss of life associated with large scale flooding of urbanized areas and new data on fatalities in the flooded area. This function can be applied to The Netherlands, as the New Orleans flood event is similar to a flood event that could occur in The Netherlands due to breaching of flood defences leading to the rapid flooding of low-lying areas up to several metres of water depth. A previous function was based on data from the storm surge disaster in The Netherlands, which occurred decades ago in 1953. It is expected that the data for New Orleans gives a better representation of the loss of life due to a flood in a modern developed and densely populated area. Moreover, the models derived for The Netherlands and New Orleans have been compared and when they are applied to estimate the loss of life for the same set of flood scenarios the outcomes deviate less than 20% (Maaskant, 2007).

By combining information regarding the spatial distribution of fatalities,[1] estimates of the exposed population and information on flood depths, a functional relationship between the inundation depth and the mortality could be determined. A visual representation of this depth related mortality function is given in Fig. 1. The points in the figure are observations of the mortality and inundation depths in different neighbourhoods of New Orleans. A best-fit trend line has been derived from these observations. Although a clear trend can be observed from the dataset, there is considerable uncertainty associated with this mortality function. A major reason for the deviation between the different observation points, is the fact that they have been established for different neighbourhoods, where differences may exist in evacuation and/or shelter. However, there is at present no additional information available on these effects. The uncertainties in the mortality function are indicated in Fig. 1 by the 5% and 95% confidence intervals. These bandwidths have been derived by statistical analysis of the available observations, while assuming that all curves should lead to a mortality of zero for an inundation depth of 0 m. The confidence intervals in Fig. 1 show that mortality numbers for a given inundation depth can be given with ±55% accuracy on average.

[1] This data has been collected by the Louisiana State University in cooperation with the Louisiana Department of Health and Hospitals and the medical examiners office (Boyd, 2006).

3. Case study area and data

3.1. *General characteristics*

The population of The Netherlands has been growing at an average rate of 0.7% per year and the number of persons per household has declined in the last 30 years (SCP, 2004). Consequently, the number of households has increased, from 6 million in 1990 to 7 million in 2003, and will increase to a projected 7.9 million in 2020, and to 8.3 million in 2035 (SCP, 2004). Because of these changes there is an increasing demand for residential areas. Especially in the western part of the country these new residential areas are developed in flood prone areas, often around or below sea level. For example, it has been decided to build 4000 houses in the Westergouwe polder near the city of Gouda. With an average elevation of approximately 5.80 m below mean sea level this is one of the lowest areas in The Netherlands. Unsurprisingly, there has been a lot of societal and political discussion regarding the desirability of the development of such low-lying areas. Yet, these low-lying areas are often the only places left in the western part of The Netherlands that are available for development, and local needs drive the creation of new urban areas in these polders.

The study area of South Holland is threatened by floods from the sea and river. The threat from the sea is caused by storms at the North Sea that lead to the occurrence of storm surges. The Maeslantbarrier has been constructed east of Hoek van Holland, in order to prevent storm surges form entering the river on the south side of the area (Fig. 2). When a certain threshold in water level is expected to be exceeded, this barrier will be closed, to prevent that storm surges at sea could lead to high water levels in the river and estuarine areas that are in open connection with the sea.

To analyse the risks under the current flood defence system in The Netherlands, the Dutch government has initiated the Flood Risks and Safety (FLORIS) project (Rijkswaterstaat, 2005). In this study the probabilities and consequences of flooding have been analysed for different dike ring areas in the Netherlands. A dike ring area is an area protected against floods by a single series of primary flood defences (dikes, dunes, hydraulic structures) and high grounds.

For each dike ring area a set of flood scenarios has been selected and elaborated in order to estimate the potential consequences of a flood. Each flood scenario is based on a breach at a certain location in the flood defence system (or a set of multiple breaches), which has a particular probability attached to it. This breach results in a pattern of flooding, which has been simulated with a two dimensional hydrodynamic model. This simulation provides information on the flood depth, flow velocity, arrival time and rise rate. These outcomes are used to assess the consequences (economic damage and loss of life). In this study the flood depths are used as input for the mortality function to estimate the loss of life. For the study area (South Holland) 10 flood scenarios have

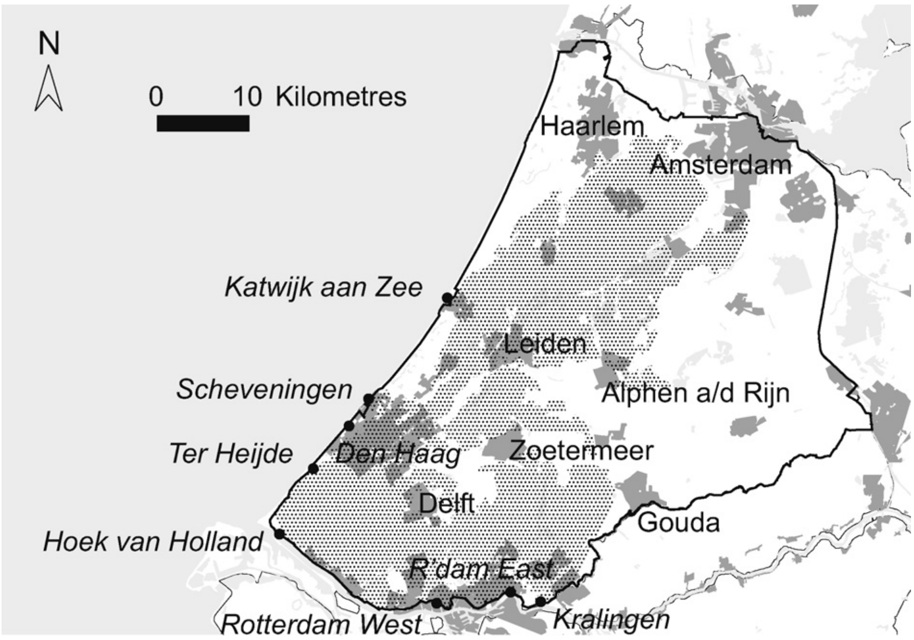

Fig. 2 – Overview of South Holland. Flood prone areas in South Holland are shown by the dotted area, and current major urban areas are shown in grey. Breach locations that are used for analysis of flood scenarios are indicated in the figure with dots.

been analysed that give insight in the possible patterns of flooding in the area and their consequences for economic losses and loss of life (Rijkswaterstaat, 2006a,b). These 10 flood scenarios represent both river and coastal floods. Fig. 2 gives an overview of the breach locations that have been used to develop the flood scenarios. A combination of 10 flood scenarios gives the total flood prone area for South Holland (the hatched area in Fig. 2).

As this analysis involves a very complicated topic, which is the occurrence of fatalities due to flooding under potential future conditions, there is a necessity to simplify and generalise a number of factors. We make a number of major assumptions for this analysis, and we have listed these in Table 1. Below, we discuss these assumptions.

3.2. *Socio-economic change*

Data on the spatial distribution of the population has been obtained from the Land Use Scanner model (RIVM, 1997; Schotten et al., 2001) that calculates future land use patterns based on spatial claims and suitability for different land use types. The choice of land use depends on individual choice behaviour, based on microeconomic theory. Spatial land use data from this model is available for the years 2000 and 2040 and therefore these have been used as reference years. The Land Use Scanner data is provided at a horizontal spatial resolution of 100 m × 100 m and this is also the resolution that has been used to make the loss of life estimates. The model calculations are based on estimated land use under a socio-economic scenario, the Global Economy (GE) scenario, which is one of a set of four scenarios recently published for use in economic and environmental policy studies (WLO, 2006). This scenario assumes a continuing growth of the national population of 0.5% per year, and a relatively rapid economic growth of 2.6% per year. The other three scenarios assume less population growth (0–0.4%) and a smaller economic growth (0.7–1.9%). Therefore this GE scenario can be regarded as 'high' scenario in which population and capital are projected to accumulate most rapidly in the coming decades. The four WLO scenarios have been specifically developed for the Netherlands, but have some similarities with the IPCC SRES scenarios (IPCC, 2000). The Global Economy scenario that we are applying would resemble an SRES A1 world.

The projected land use pattern from the Land Use Scanner model distinguishes three types of residential areas with different types of population densities: high density, low density and rural area. The densities for these three residential areas are determined by the mean population density for The Netherlands. As population densities in the urban areas in the case study area are higher than high-density population areas elsewhere in The Netherlands, the actual high, low and rural densities need to be determined for the case study area in South Holland. Therefore additional information is used from Statistics Netherlands (CBS)[2] on the actual current neighbourhood and city populations. With this information the densities for the three types of residential areas are calculated for the case study area.

3.3. *The impact of climate change on flood characteristics*

Global climate change leads to a rise in sea level and to an increase in the probability of high river discharges. Therefore the hydraulic loads on the flood defence system are projected to increase. These higher hydraulic loads could lead to an

[2] Wijk- en buurtkaart, version 2006.

Table 1 – Assumptions about future risk characteristics in dike ring 14 and some notes on uncertainties.

Socio-economic characteristic	Change in 2040	Note
Population growth (national)	0.5% pa	High estimate
Increase in population	33%	High estimate
Increase in exposed population	50%	High estimate
Flood characteristic	**Change in 2040**	**Note**
Sea level change	+0.30 m relative to 2000	High estimate
Inundation level of storm surge	+0.15 m relative to 2000	High estimate
Flood probability (storm)	Increase by factor 2.37	High estimate
Flood probability (river)	Increase by factor 2.1	High estimate
Flood extent	Remains same as in 2000	
Improved flood prevention	Not considered	Can reduce flood probability
Evacuation	0%	Could possibly reduce exposed population by up to 20%

increase of the probability of flooding if no adjustments are made to the flood defence system. In addition, higher inundation depths could occur when the flood defences breach and could thereby lead to more severe consequences. The effects of these factors will be investigated separately and in combination. To analyse the effects of flooding in the future several assumptions had to be made regarding uncertain developments in the future. It was chosen to analyse the consequences and risks for the year 2040, and several studies provide information regarding population development and climate change for this year.

For the determination of the future potential number of fatalities in the year 2040 the assumption has been made that the flooded areas for the flood scenarios from the FLORIS study will not change considerably. The assumption is that these scenarios give a representative indication of the possible flood scenarios both for the current situation and for the year 2040. This means that the main characteristics of the flood defence system, terrain topography and flood pathways would not change substantially in the future. In fact, plans have recently been proposed to change the terrain topography of polders by creating compartments or dwelling mounds in order to reduce flood risks. We stress that changes in flooded areas could considerably change the loss of life estimates, although to an unknown extent. But such measures are difficult to foresee now, and are therefore not taken into account. Our estimates are therefore valid under unchanged circumstances with regard to flood protection measures.

In this study we focus on relative changes in the number of fatalities and event mortality. The effects of evacuation and shelter are not taken into account. This leads to an exposed population of 100%. We expect that evacuation will not improve considerably in the future, and therefore would not affect the projected exposed population. Other studies do include evacuation and shelter rates, which vary for South Holland from 60 to 80% (Klijn et al., 2007). However, another study using a traffic model suggested that evacuation possibilities are very limited in The Netherlands, estimating evacuation rates to be between 1 and 20% (Rijkswaterstaat, 2006c). Therefore, evacuation would probably not have a great mitigating effect. Assuming no evacuation would result in an overestimation of the actual exposed population. We can however not completely exclude a potential effect of evacuation; successful evacuation would imply a 1–20% decrease in the exposed population given in this paper (Table 1).

Regarding the impacts of climate change on flood probabilities and increased inundation depths, we make the following assumptions: relative mean sea level (including subsidence) is expected to increase by 0.30 m for the year 2040, relative to 2000. This is a relatively high estimate, falling at the higher end of the range of 0.15–0.35 m projected for 2050 relative to 1990, as reported by the Royal Netherlands Meteorological Institute (KNMI, 2006). Choosing a high estimate for sea level rise is however consistent with our scenario of high economic growth and population growth. New information that has recently become available from the Deltacommissie (2008) estimates the high end of relative sea level rise to be between 0.65 and 1.30 m in 2100, considering more warming at the end of the century, and increased expansion of seawater and more rapid ice sheet loss of Greenland and Antarctica. But for mid-century, the Deltacommissie assumes the estimates from KNMI (2006) still to be valid.

A 0.30 m increase in sea level does not automatically imply a 0.30 m increase in inundation levels. For a typical coastal flood it is assumed that a breach occurs when the water level reaches 4.65 m +NAP, this water level is also used in Rijkswaterstaat (2006a), and that water starts to flow into the study area. After approximately 25 h the storm surge has disappeared, but the breach is still in open connection to the sea. We assume that further inflow will only occur when the water level is above mean sea level. The difference in surface area under the storm surge graph between the years 2000 and 2040 can be used to estimate the extra volume of water that enters the area. It is assumed that after 5 days the breach is closed and that no more water will enter the area. In these 5 days it can be calculated from the typical flood wave that the total flood volume increases by 20% due to the higher water levels at sea. This extra 20% of volume is distributed over the flooded area per scenario, and this leads to an increase in flood depth that varies per scenarios between 0.1 and 0.2 m. In this study an average increase in flood depth of 0.15 m due to sea level rise is therefore used for the coastal flood scenarios (numbers 2–7 and 10).

For the river flood scenarios (numbers 1, 8 and 9), the hydraulic load is determined by the combination of water levels at sea and in the river. We assume that, in case of high water at sea, the Maeslantbarrier is always closed. Because of this closure, the sea level rise of 0.30 m does not affect the water levels in the river system under storm surge conditions.

To determine the new probabilities for the 10 scenarios under climate change, we assume that there will not be any improved flood prevention through dike strengthening or heightening or increased nourishment of dunes along the coast. This is a very important assumption, and indicates what would be the consequences of not improving the flood defences and/or updating the safety standards.

In The Netherlands dikes are designed to withstand a design water level with a certain probability of occurrence. Because of the above assumption of unchanged (physical) flood defences and the effects of sea level rise the probability of occurrence of the design water level will increase. It is assumed that the failure probability of the flood defences increases with the same factor as the increase in the probability of occurrence of the design water level. This factor is applied to estimate the probabilities for the coastal scenarios in a situation with sea level rise.

Currently the design water level at Hoek van Holland is set at 5.75 m +NAP, which coincides with the water level that occurs once in 10 000 year (probability of 10^{-4} per year) in the year 2000. When shifting up the water level line by 0.30 m the probability that corresponds with this design water level (5.75 m) for the year 2040 is once in 4220 year (probability of 2.37×10^{-4} per year). The factor between the two probabilities is approximately 2.37. It is assumed that the probabilities of the seven coastal flood scenarios will increase with the same factor.

The increase in probability for river floods is determined in a different way. The frequency of occurrence of the design discharge will increase. For a probability of once in every 1250 years the discharge is 16 000 $m^3 s^{-1}$ in the current situation. The relationship between river discharge and probability for the year 2040 is derived from data in Rijkswaterstaat (2007).[3] When the design level of the discharge would be kept at 16 000 $m^3 s^{-1}$, the probability increases by a factor 2.1 (from 1/1250 to 1/600). This factor of 2.1 will be used to estimate the increase of the probability for the three river flood scenarios. As we assume that the height of dikes (that determine the maximum inundation depth) will not change, it follows that the flood depths due to river flooding will not change.

4. Results

4.1. *Analysis of the increase of the number of fatalities due to population growth*

In the year 2000 South Holland had approximately 3.6 million inhabitants. According to the projected land use patterns under the Global Economy scenario this number will increase to about 4.8 million people in the year 2040, which is an increase of 33%. Fig. 3 gives an overview of the projected development of the urbanised areas in South Holland.

To investigate the effect of this population increase on the loss of life the 10 flood scenarios have been analysed for South Holland. Table 2 lists the breach locations for the different flood scenarios and the resulting exposed population for the years 2000 and 2040. It can be seen that the number of people exposed increases for the year 2040. Compared to the total population increase of 33% of the total area, the increase in the number of people potentially affected by flooding is higher. The increase of the number of inhabitants in the areas affected by the 10 flood scenarios ranges from 54 to 106%, the average increase is 72%. Population growth in South Holland is projected to take place mainly in areas that could be affected by flooding.

By combining the flooded areas from the 10 scenarios the total number of people that can be potentially exposed to a flood can be determined. For the year 2000 the total number of people that could be exposed to a flood is approximately 1.4 million. In the year 2040 this will increase to approximately 2.1 million people, this is an increase of 50%. This number differs somewhat from the 72% mentioned above, because some of the areas can be flooded under more than one scenario. Still, the increase in the potentially exposed population in flood prone areas is significantly higher than the 33% population increase for the entire area.

For the year 2040 the loss of life is estimated with the method described in Section 2. In this estimation the local developments, such as population growth, have been taken into account. In these first estimates it is assumed that the flood scenarios remain unchanged and that there is no effect of sea level rise. Table 3 presents the fatality estimates for the years 2000 and 2040 in the second and third columns. Listed in the sixth column is the relative change in the event mortality, i.e. number of fatalities relative to the exposed population, per flood scenario for the situation with population change only.

Scenarios four and five show more than doubling of the estimated fatalities in 2040, compared to the estimate for 2000. This increase is determined by the location of the population growth relative to the locations of the breaches and the flooded areas for these scenarios. Fig. 4 shows the relative increases of the population and the estimated number of fatalities. In this figure it can be seen that for 6 out of 10 scenarios the increase in the number of fatalities is smaller than the population growth (i.e. the points lie below the 1:1 line). This means that for these scenarios the average event mortality does not increase as rapid as local population growth. For the remaining four scenarios the points do lie above the 1:1 line, indicating that the event mortality increases more rapidly than local population growth.

4.2. *Increase of the number of fatalities due to sea level rise*

To incorporate the sea level rise in the loss of life estimation we made the assumption that the flood depths for coastal flood scenarios will increase by 0.15 m by the year 2040. This increase is added to the flood depths that have been estimated for the

[3] The data in Rijkswaterstaat (2007) is actually projected data for the year 2050 but for this study it is assumed to be valid as well in 2040.

Fig. 3 – (a and b) Overview of population density in South Holland in 2000 and projected density in 2040 (source: Land Use Scanner).

year 2000. It is assumed that the flood depths do not change for river flood scenarios, as they would not be affected by the rise in sea level. Table 3 shows in the fourth column the effect of sea level rise on the total number of fatalities. Results show that the estimated numbers of fatalities increase for most of the scenarios because these are associated with coastal flooding. For the river flood scenarios (numbers 1, 8 and 9) the number of fatalities does not change. This is because the Maeslantbarrier prevents the high sea water levels from entering the river system under storm surge conditions.

Table 2 – Exposed population in the flooded area per flood scenario, assuming a situation without evacuation and shelter.

Scenario [breach locations]	Exposed population 2000	Exposed population 2040	Change [%]
1. Rotterdam Kralingen	239 124	404 786	69
2. Den Haag-Boulevard	108 307	183 530	69
3. Den Haag-Scheveningen	138 772	230 435	66
4. Katwijk	261 528	537 944	106
5. Hoek van Holland	102 767	206 643	101
6. Katwijk and Den Haag	333 168	581 486	75
7. Den Haag and Ter Heijde	653 950	1 084 085	66
8. Rotterdam West	121 103	199 616	65
9. Rotterdam Oost	169 897	262 472	54
10. Katwijk, Den Haag and Ter Heijde	1 104 032	1 749 762	58

Table 3 – Number of potential flood fatalities in 2000 and 2040, and event mortality change for the 10 scenarios in 2040.

Scenario	Fatalities 2000	Fatalities 2040			Event mortality change [%]		
		Population change	Sea level rise	Population change and sea level rise	Population change	Sea level rise	Population change and sea level rise
1	1853	3039	1853	3039	−3	0	−3
2	231	331	305	453	−15	32	16
3	251	368	351	525	−12	40	26
4	746	1614	954	2053	5	28	34
5	177	396	247	544	11	40	53
6	942	1737	1193	2196	6	27	34
7	3690	6103	4372	7128	0	18	17
8	336	414	336	414	−25	0	−25
9	611	838	611	838	−11	0	−11
10	5324	9398	6005	10468	11	13	24

4.3. *Increase of the number of fatalities due to the combined effect of population growth and sea level rise*

Table 3 shows the number of fatalities for the years 2000 and 2040 in the fifth column. As can be seen there is a drastic increase in the loss of life for scenarios four and five. These two scenarios are coastal floods with breaches near Katwijk and Hoek van Holland (see Fig. 2 for locations), affecting a large number of densely populated residential areas. Table 2 shows that the relative population increase for these two scenarios is also higher than for the other eight scenarios. So the additional increase in the loss of life in comparison to the other flood scenarios can partly be explained by the extra population growth in the areas exposed to flooding in these two scenarios.

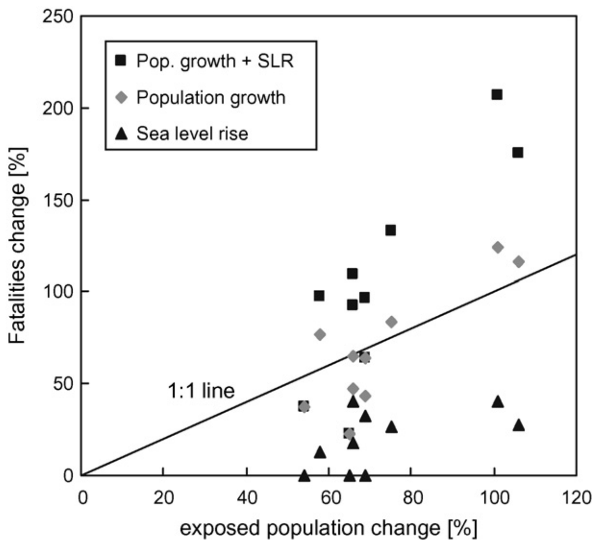

Fig. 4 – Loss of life estimates for the years 2000 and 2040, under scenarios of population growth, sea level rise, and the combined scenario.

The results from Table 3 are presented in Fig. 4. This figure shows clearly that for most scenarios the increase in fatalities is (much) larger than the increase in population growth, especially when the impacts of population growth and sea level rise are combined.

4.4. *Changes in societal risk level*

The preceding paragraphs have investigated the possible increase of the potential consequences due to flooding. In this section we consider the risk level, i.e. the combination of probability and consequences. This means that also the effect of sea level rise on the flooding probability is examined. Following the general assumptions (see Section 2) a situation is considered in which no additional measures are taken (e.g. strengthening of the sea defences) to reduce the impacts of sea level rise and other effects of climate change on flooding probabilities.

The concept of societal risk is based on the probability of an accident leading to a certain number of fatalities. The *FN*-curve is generally used to determine societal risk (e.g. Jonkman et al., 2003). An *FN*-curve gives the probability of exceedence (per year) of accidents with a certain number of fatalities. Both

Table 4 – Number of potential fatalities and annual probabilities for the 10 scenarios in 2000 and 2040.

Scenario	Fatalities 2000	Probability 2000	Fatalities 2040	Probability 2040
1	1853	1.37×10^{-4}	3039	2.88×10^{-4}
2	231	1.19×10^{-4}	453	2.82×10^{-4}
3	251	7.62×10^{-5}	525	1.81×10^{-4}
4	746	2.44×10^{-5}	2053	5.78×10^{-5}
5	177	1.15×10^{-5}	544	2.73×10^{-5}
6	942	8.35×10^{-6}	2196	1.98×10^{-5}
7	3690	7.22×10^{-6}	7128	1.71×10^{-5}
8	336	4.90×10^{-6}	414	1.03×10^{-5}
9	611	3.64×10^{-6}	838	7.64×10^{-6}
10	5324	2.23×10^{-6}	10468	5.29×10^{-6}

axes of the *FN*-curve are generally shown on a logarithmic scale. In this case the accident frequency *F* is the probability that a certain flood occurs, and *N* is the number of fatalities.

The *FN*-curve can be constructed with the use of the probabilities and number of fatalities from the 10 flood scenarios (see Table 4). In Fig. 5 the *FN*-curve for the year 2000 is shown for South Holland, see also Jonkman et al. (2008b) for further background. The curve will shift due to population growth and changes in flood probability due to climate change. Table 4 lists the change in number of fatalities and the new probabilities for the 10 scenarios. The population growth leads to an increase in potential fatalities, shifting the curve to the right and because of the sea level rise, the probability that a flood occurs also increases, moving the curve upward.

The expected number of fatalities can be found by summing the product of probability and consequences for the 10 flood scenarios. For the year 2000 the expected value of the number of fatalities is 0.37 per year. For the year 2040 we use the altered probabilities for flooding, as explained in Section 3, and the estimates for the increase in the number of fatalities due to population growth and urban development in low-lying areas, as explained in previous sections. In our estimate, in 2040 the expected number of fatalities becomes 1.46 fatalities per year. This is an increase of more than a factor 4 and it is caused by increases in the probability of flooding, increased inundation levels from storm surges due to sea level rise, and an increase in the potential number of fatalities due to population growth. So within the considered period, the

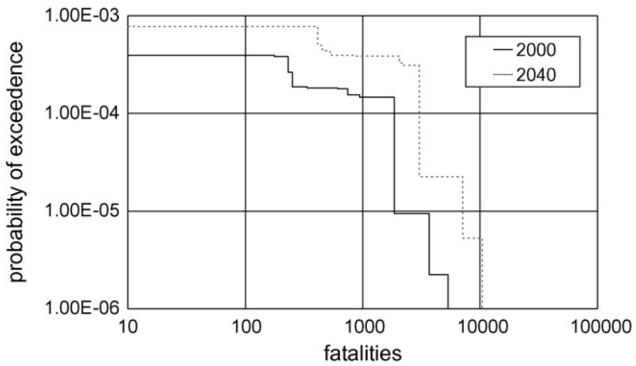

Fig. 5 – *FN*-curve for loss of life due to flooding in South Holland for the years 2000 and 2040.

population growth and sea level rise could lead to a quadrupling of the expected number of fatalities, if no additional risk reducing measures are taken.

5. Discussion

Table 5 lists the number relative changes of estimated fatalities in 2040 under population growth, sea level rise and the two factors combined. Upper and lower bounds are given, which consist of the maximum and minimum fatality numbers found for the 10 different flood scenarios. As can been seen in the first three rows of Table 5 both the sea level rise and the population growth cause the number of fatalities to increase (by 68 and 20%, respectively), but the impact of population growth is considerably larger than the sea level rise. This illustrates the possible increase of the flood risk in low-lying coastal areas due to population growth. This increase in flood risk can be much higher than average national growth rates of population and economy. The combination of sea level rise and population growth leads to an increase of the number of fatalities of 103%. However, it is also important to express the increase in potential fatalities relative to the total number of inhabitants in the dike ring area (3.6 million in 2000 and 4.8 million in 2040), in order to estimate the relative increase of flood casualties. The last three rows in Table 5 show the share of flood victims estimated per 1000 inhabitants in the dike ring area, assuming occurrence of flooding. This ratio increases from 0.39 to 0.51 (29%) due to the disproportionate increase of population in deep lying areas. Sea level rise alone also leads to an increase the estimated flood victims per 1000 inhabitants, from 0.39 to 0.45 (15%), due to an increase in water depths in the flooded areas. Sea level rise and population growth combined lead to a relative increase of potential casualties from 0.39 to 0.57 (47%) on average.

In The Netherlands there is a discussion on the risks of building in deep polders and the resulting increase of the possible consequences of flooding. In the location that is situated between Delft and the north side of Rotterdam (Fig. 6) the elevation varies between 3 and 4 m below mean sea level. According to the land use projections, this area is likely to be developed into a residential area between the years 2000 and 2040. While the exposed population is projected to increase by 102% (from approximately 111 536 to 225 311), the impact of these developments on the number of fatalities is an increase of 158% (from an estimated 537 to 1476). Also for this location the increase in fatalities is higher than the growth in population. The mortality increases by 27% by 2040 for this location.

The numbers presented in this paper are an indication of the potential future increase of the number of fatalities. There are several uncertainties with respect to the variations in the flood scenarios. The scenarios are assumed to be comprehensive, but given the small number of scenarios it may be that certain areas are overlooked, or maximum inundation levels are underestimated. However, this would only lead to an underestimate of the baseline and future absolute numbers of potential fatalities. The relative change in potential fatalities is less likely to be affected. There is also uncertainty with respect

Table 5 – Estimated changes in number of fatalities in 2040.

	Lower bound [%]	Upper bound [%]	Average fatality change [%]
Population growth	23	124	68
Sea level rise (0.30 m)	0	40	20
Population growth and sea level rise	23	207	103
	Lower bound [per 1000 inhabitants]	Upper bound [per 1000 inhabitants]	Average fatality change [per 1000 inhabitants]
Year 2000	0.05	1.45	0.39
Population growth	0.07	1.93	0.50
Sea level rise (0.30 m)	0.07	1.67	0.45
Population growth and sea level rise	0.08	2.15	0.57

Fig. 6 – (a and b) Population growth in the area between Delft and the North of Rotterdam.

to the effect of sea level rise on the increase of inundation depth in the affected areas. Finally, there is also an uncertainty associated with the mortality function that has been applied in these estimates. Despite these uncertainties it is found that population growth and sea level rise can lead to a significant increase in the number of fatalities.

These results are valid only for a situation in which no measures are executed to limit the increase of consequence and risk levels. Therefore the results can be considered as conservative estimates of the possible increase of the risks. The principle of upgrading flood defences is already included in the current Dutch safety standards. Every 5 years the design water levels (see also Section 2) are updated to account for new insights in the status of hydraulic boundary conditions, including the effects of sea level rise and climate change on storm surge probabilities and peak river runoff. In reality, several measures could limit the growth of the risk level. For example, the improvement of emergency management could reduce the number of fatalities, and preventive measures could reduce the probability of a flood disaster. This also indicates that the current trend of a declining number of fatalities due to natural disasters (see Section 1) does not necessarily need to reverse because of ongoing population growth and climate change. The results could contribute to decision-making regarding adaptation to the effects of climate change and the prevention and mitigation of flood impacts. Results show that the consequences and risks are expected to increase significantly without measures and this issue needs to be addressed. A combination of strategies could be considered, including preventive measures, as well as measures such as risk zoning of new developments in flood prone areas.

A few other studies have investigated possible changes in the number of fatalities over time. General discussions are found in Jonkman (2007) (Section 8.8.3) and McClelland and Bowles (2002), concluding that it is likely that mortality rates have remained fairly constant over time, and would possibly remain so if there are no significant changes in building quality, and warning and evacuation. Some other studies in The Netherlands analyse projected developments in the number of fatalities, see for instance Klijn et al. (2007). In that study a simplified method is used to determine the expected number of fatalities for both the present situation and the future. For the same study area, one estimate of the loss of life is given by assuming certain values for the number of inhabitants, the fraction evacuated and the average mortality fraction. For South Holland the study reports an average estimate of 575 fatalities with lower and upper bounds of 37 and 4380. Our results are of the same order of magnitude: an average of 940 fatalities and lower and upper bounds of 180 and 5300 (see Table 3).

For the future scenario, the study by Klijn et al. (2007) used an overall growth factor to determine the fatalities in 2040. This growth factor is based on the changes in number of inhabitants and on the changes in land use, for example new urban area development. For South Holland this factor is 1.2, so according to their study the number of fatalities would increase by 20% between 2000 and the year 2040. Compared to the relative increase in this study this seems relatively low. In this study the increase in fatalities due to increase in population and change in land use is on average 68% (Table 5). The difference can be explained by the fact that in this study 10 flood scenarios are used and for each scenario the impact of local changes in land use and population increase have been analysed in more detail. Our analysis has shown that most of the population increase and new housing is situated in areas that are likely to be affected by floods. This indicates the crucial importance to take into account the specific locations of the population growth in combination with detailed flood scenarios.

Overall, the presented findings show the potential limitations of studies that project future flood risks based on average growth percentages of the population only. In such analyses the effects of the location of population developments and the changes of flood patterns due to sea level rise have not been considered. Therefore, it seems that an approach that takes account such developments by means of data regarding land use change and flood scenarios is to be preferred. This allows identifying the effects of local developments and changes in flood conditions on future exposure and the number of potential fatalities.

6. Conclusions and recommendations

In this article the temporal development of flood risks to people has been examined for a major flood prone area in The Netherlands (South Holland). This was done by applying a loss of life model with input from different flood scenarios and projections of population growth and its spatial distribution.

The population growth in areas that are exposed to floods is higher than the average population increase in South Holland (+50% in areas that could be affected by flooding vs. +33% in the entire area). This is one of the main reasons why the estimated number of fatalities increases more rapidly than the average population growth rate for The Netherlands. On average the number of fatalities increases with 68% in 2040 under a relatively high growth scenario for population (see Table 5). The increase of the sea level leads to a systematic increase in mortality for all coastal flood scenarios. A sea level rise of 0.30 m is expected to lead to an average increase in fatalities of approximately 20%. Under a combination of sea level rise and population growth the number of fatalities is projected to double (increase by approximately 103%).

The impacts of climate change on sea level rise and increased river discharges could also affect the probability of flooding if no preventive measures are taken. An analysis of societal risk showed that the probabilities and consequences could increase both with a factor 2. This leads to an increase in the expected number of fatalities of approximately a factor 4, if no preventive and risk reducing measures are taken. It is noted that this not a very realistic assumption, as the Dutch flood defence policy includes a periodic assessment of the safety of the system to anticipate changes, such as sea level rises. The presented result is thus a conservative and upper bound estimate of the increase of the risk level.

Focusing on smaller low-lying areas such as Rotterdam Noord (Fig. 6) it can be seen that building residential areas in deep polders is expected to lead to a significant increase in the mortality (27% for the studied area). This increase in mortality is mainly caused by the population growth in these deep polders and not by the sea level rise, because in deep polders that are already at risk from flooding the impact of an additional increase in inundation depth on fatalities is relatively small. Risk reducing measures, such as improving evacuation, construction of shelters, dike heightening, construction of compartment dikes and dwelling mounds can help to reduce the increase of consequences in these low-lying locations. The effect of these measures has not been assessed in this study, but their effects on potential flood victims are definitely worth considering in future risk assessments.

In comparison with studies that use general growth percentages to analyse the future risks, the presented approach has the important benefit that it takes into account the actual spatial effects of land use change and changes in flood conditions. As it is found that the increase in fatalities is much larger than the increase in population growth, the application of an averaged growth factor as applied by other studies (e.g. Klijn et al., 2007) is not preferable. It is therefore recommended to use the presented approach in strategic scenario studies. Apart from the risks to people, projections of developments in economic damage could be analysed in a similar way.

A wider implication of our results is that for expected loss of life it clearly matters where people are located. This would not be unique for The Netherlands, but apply to most major urban coastal areas around the world. The trends in risk that have been reported in this paper cannot be directly extrapolated to other regions, because the developments in flood risk will depend on local conditions, such as local topography and projected locations of population growth. However, very similar developments are likely to take place in other areas in the world, in particular in developing countries where population growth is even more rapid, and where consequences for flood risks will be more severe. As recent studies suggest (RPB, 2007), strategies aimed at limiting or reducing potential loss of life therefore need to take into account the consequences of certain spatial planning decisions that affect exposure and therefore risk.

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