AMBIO (2012) 41:180–192
DOI 10.1007/s13280-011-0193-x

REPORT

Assessment of the Netherlands' Flood Risk Management Policy Under Global Change

Frans Klijn, Karin M. de Bruijn, Joost Knoop, Jaap Kwadijk

Received: 27 January 2011 / Revised: 6 September 2011 / Accepted: 6 September 2011 / Published online: 18 October 2011

Abstract Climate change and sea level rise urge low-lying countries to draft adaption policies. In this context, we assessed whether, to what extent and when the Netherlands' current flood risk management policy may require a revision. By applying scenarios on climate change and socio-economic development and performing flood simulations, we established the past and future changes in flood probabilities, exposure and consequences until about 2050. We also questioned whether the present policy may be extended much longer, applying the concept of 'policy tipping points'. Climate change was found to cause a significant increase of flood risk, but less than economic development does. We also established that the current flood risk management policy in the Netherlands can be continued for centuries when the sea level rise rate does not exceed 1.5 m per century. However, we also conclude that the present policy may not be the most attractive strategy, as it has some obvious flaws.

Keywords Climate change · Sea level rise · Flood risk · Vulnerability · Tipping point

INTRODUCTION

Anthropogenic climate change and the related sea level rise feature among the most studied and debated environmental issues of the last decade. In computer simulations, e.g., by NASA, many low-lying coastal plains and deltas—including the Netherlands—are almost completely being flooded in the course of the twenty-first century. Such simulations may sustain the political call for global action to mitigate climate change by reducing the emissions of greenhouse gasses, but they are far from likely. For as mitigation requires concerted action on a global scale, many countries also prepare for the apparently inevitable and draft adaptation policies (Claessen et al. 2009). Such adaptation policies may reduce the impacts of climate change and sea level rise.

As a relatively vulnerable country, the Netherlands with its over 55% flood-prone area is among the front-runners in attention for climate change and sea level rise, and puts lots of effort in analyzing the problems and developing adaptation policies. After a number of preliminary studies, the government started the national program Adaptation of Spatial Planning to Climate Change (ARK), in which it was established that in our maritime temperate climate flood risk management and freshwater resources management face the largest challenges (Kwadijk et al. 2006).

Moreover, the government solicited advice on adaptation policies for flood risk management and freshwater resources management from an independent committee (Delta Committee, 2008). This resulted in the advice to start a Delta Program dedicated to defining and implementing a long-term adaptation strategy for integrated water management with emphasis on the large rivers, estuaries, Lake IJssel and the coast in view of a rising sea level and changing river discharge regimes. In this program, earlier policy initiatives, such as Water Safety 21st Century, have been incorporated. The drafting of this adaptation strategy is being scientifically supported by dedicated studies and by a 50 million euros research program 'Knowledge for Climate (Change)'.

Within this context, we assessed the influence of climate change on the future development of flood risk. This required that we first had to assess the flood risk—economic risk and fatality risk—for the country as a whole and for the current situation (Klijn et al. 2004a), as this was yet unknown. Next, we assessed the future development of these risks, as driven by climate change as well as demographic and economic developments, applying future scenarios (Klijn et al. 2007, 2010a). For the risk assessments, we applied concepts as developed within the EU-integrated project FLOODsite (FLOODsite 2009; Samuels and Gouldby 2009). We also addressed the question whether the current flood risk management policy can be sustained in view of possible climate change scenarios (Kwadijk et al. 2008, 2010), or whether it should be adapted.

CLIMATE CHANGE AND RELEVANT HYDROLOGICAL CHANGES

Climate change—and the related sea level rise—is generally regarded as one of the main reasons to reconsider flood risk management policies for the future. It is also widely accepted that climate change and sea level rise accelerate by human activities that influence the atmosphere (IPCC 2001, 2007). The rate of change is very uncertain, however, and so is the direction of some related hydrological effects which depend on the (re)location of large-scale atmospheric circulation patterns. This inherent uncertainty is tackled by not issuing one prognosis, but by distinguishing various possible future scenarios. IPCC (2007), for example, estimates the range of global mean sea level rise to be between 0.18 and 0.59 m at the end of the twenty-first century, assuming temperature rises between 2 and 4°C. Based on these IPCC-scenarios for global warming and global sea level rise, the Royal Netherlands' Meteorological Institute derived four scenarios for the Netherlands (KNMI 2006), taking into account these different temperature rises, as well as possible changes in global circulation.

KNMI (2006) recognizes four different scenarios, either moderate (G) or warm (W), and with (+) or without major change in the circulation pattern over Western Europe (Table 1). Based on the temperature rise, expectations are derived for mean precipitation, potential evapotranspiration, daily rainfall, etc. The global sea level rise is translated into the sea level rise along the Netherlands' coast, taking into account regional differences and large-scale geological movements. KNMI thus estimates the mean sea level along the Netherlands' coast at the end of the twenty-first century to be between 0.35 and 0.85 m higher than at present, but for a possible upper limit higher values apply, of up to 1.3 m (Vellinga et al. 2009). All these translations rely on knowledge about causal relationships in the climatic, oceanographic, and geological realm and are considered fairly accurate. They yield the—by itself relevant—mean sea level, and can also be used to derive the key variables for establishing coastal flood risk, viz., storm surge level and significant wave height.

For the rivers, however, we need scenarios on the change in river discharge regime, and especially flood levels. The climate change scenarios of KNMI were therefore used to calculate mean monthly discharges of the Rhine and Meuse Rivers (Van Deursen 2006). Thus also four scenarios for river discharge regime were obtained (Fig. 1) which reveal that the mean winter discharges are likely to become substantially higher, whereas the mean summer discharges may become significantly lower, especially in the Rhine River. Unfortunately, for flood risk the monthly mean discharges are not very relevant, as only extreme floods are hazardous.

Especially for the flood-protected areas in the Netherlands, we need to know the change in exceedance probability of the design flood, or instead the river discharge to be expected with the same exceedance probability as the present design flood. The design flood is the discharge for which the embankments are designed, which is the 1:1250 per year discharge for the Rhine and Meuse Rivers. By various approaches it has been attempted to derive the change in these 1:1250 per year design discharges.

A first method relies on simply 'pressing' the increased precipitation and evapotranspiration increases onto the Rhineflow and Meuseflow models of the catchments (rainfall-runoff models based on the HBV model (Lindström et al. 1997)), in order to produce 100 years of mean daily discharges. A subsequent frequency analysis of the yearly maxima yielded a design discharge between 18 500 and 21 500 $m^3\ s^{-1}$ (each ± 2500 $m^3\ s^{-1}$) for the Rhine River in 2100—depending on scenario—against the present 16 000 $m^3\ s^{-1}$. As such discharges will, however, cause extensive overtopping of embankments upstream in Germany, it is estimated that no more than 18 000 $m^3\ s^{-1}$ can reach the Netherlands (Lammersen 2004), and even that requires huge adaptation of the riverbed or raising the embankments in Germany.

A more sophisticated approach has been performed by Te Linde et al. (2010) with the FEWS-ED instrument and 1D hydraulic flood routing. This approach relies on a time series of 8000 years generated by drawing samples from 100 years of 'calculated weather' based on measurements adjusted to the scenarios. As Te Linde took the discharge capacity of the river into account, the result for a 1:1250 per year flood is quite similar: a maximum of about 17 500 $m^3\ s^{-1}$. It was also found, however, that the moderate climate scenario G results in no significant rise of the design discharge at all, a finding that is supported by other recent research (CHR/KHR 2010).

The above demonstrates the uncertainty we have to deal with when it comes to future climate and hydrological conditions. It thus also sustains the decision to use scenarios to establish "what, if …", and to thereby obtain insight in the present policy's sustainability.

Table 1 Four climate scenarios for 2100 (KNMI 2006)

KNMI 2100		G	G+	W	W+
	World-wide temperature rise (°C)	+2	+2	+4	+4
	Change of circulation	No	Yes	No	Yes
Winter	Mean temperature (°C)	+1.8	+2.3	+3.6	+4.6
	Coldest day each year (°C)	+2.1	+2.9	+4.2	+5.8
	Mean precipitation (%)	+7	+14	+14	+28
	Number of wet days (>+0.1 mm) (%)	0	+2	0	+4
	10- day precipitation sum exceeded once in 10 years (%)	+8	+12	+16	+24
	Highest daily mean windspeed per year (%)	−1	+4	−2	+8
Summer	Mean temperature (°C)	+1.7	+2.8	+3.4	+5.6
	Hottest day per year (°C)	+2.1	+3.8	+4.2	+7.6
	Mean precipitation (%)	+6	−19	+12	−38
	Number of wet days (>+ 0.1 mm) (%)	−3	−19	−6	−38
	Daily sum of the precipitation exceeded once in 10 years (%)	+27	+10	+54	+20
	Potential evapotranspiration (%)	+7	+15	+14	+30
Sea level	Absolute rise (cm)	35–60	35–60	40–85	40–85

G moderate, *W* warm, + with change of circulation pattern over Western Europe

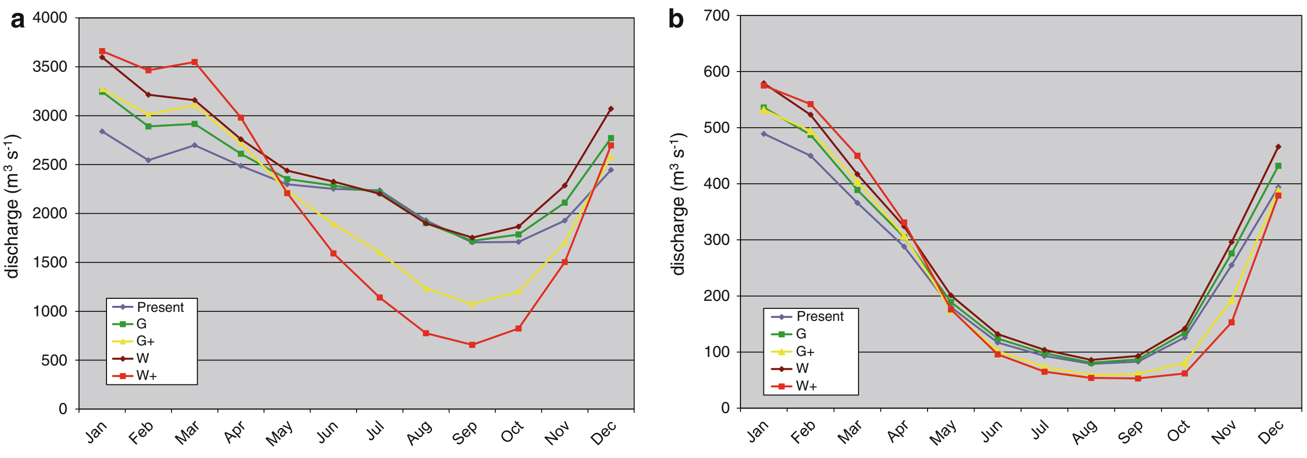

Fig. 1 Discharge regime of the Rhine River at Lobith (**a**) and the Meuse River at Borgharen (**b**) in 2100 in the various KNMI 2006 scenarios in comparison to the current regime (Van Deursen 2006)

THE PRESENT NETHERLANDS' FLOOD RISK MANAGEMENT POLICY: TIPPING POINTS

The Netherlands has a history of about 1000 years of adaptation to rising water levels and subsiding land. The subsequent inventions of windmills and mechanic pumping stations allowed the draining of peatlands—which in places sank more than 5 m—and the reclamation of land from the sea. In the course of history, thus a system of flood defenses evolved called dike-rings. Dike-rings surround flood-prone areas and are constituted by connected embankments and other flood defenses, sometimes connecting to high grounds. In the Water Law—the successor of the Law on Flood Defense—53 major dike-ring areas are defined, ranging from almost 5000 km^2 to less than 1 km^2, which cover the whole flood-prone part of the country, as well as about 40 minor dike-ring areas in the natural valley of the Meuse River.

The dike-rings protect the flood-prone areas against flooding according to pre-defined protection levels, ranging from 1:10 000 per year along the coast to 1:1250 per year along the rivers for the major dike-rings. These protection levels are based on a cost-benefit analysis (Van Danzig 1956), which was carried out after the 1953 flood disaster by the then Delta Committee for the economically most important part of the country. The results of this cost-benefit analysis were translated into protection standards for the flood defenses and subsequently extrapolated to the remainder of the country. The protection standards refer to exceedance probabilities of hydraulic loads—water level and waves—which function as design conditions. The then Delta Committee assumed that defenses designed for these conditions would hold with a probability of at least 90% certainty. This means that a 1:10 000 protection level would correspond with a 1:>100 000 flooding probability.

That the current protection standards are being met is ensured by dedicated regulations related to the Water Law. These prescribe that the hydraulic design conditions be re-established every 6 years, and that subsequently the embankments must be re-assessed on their capacity to withstand these conditions. Through this procedure, the reliability of the flood defenses and their maintenance is more or less guaranteed, whereas adaptation to changing circumstances is built-in by the recurrent re-evaluation of the design conditions. It may, therefore, be expected that the failure probability of the embankments will not increase with climate change but instead remain fairly constant—or more precisely: vary between a temporary overshoot and a next shortfall.

As the design conditions have shown a steady increase over time in the past, however, and are expected to increase further in the future, the embankments had and will have to be raised over and over again. While the land further subsides, the water levels at sea, in the rivers, and in the lakes and estuaries along the coast steadily rise. An important question therefore is: "How long can the country pursue its—inherently adaptive—flood risk management policy of flood defense?" This question was addressed by the recognition of so-called *policy tipping points* (Kwadijk et al. 2010).

Policy tipping points are defined as those moments in the future at which the current policy, be it in terms of concrete measures or comprehensive strategies, can no longer be sustained. This may be for technical reasons (simply impossible), for financial reasons (too expensive or not feasible) or for societal reasons (no longer desirable in view of the societal costs and benefits). The advantage of policy tipping points is that they can be defined in terms of the degree of change or the rate of change which the measure or strategy can cope with; for example the maximum sea level or the maximum rate of sea level rise. This means that their assessment does not depend on climate scenarios as 'modeling input', which would require their re-assessment every few years that a new set of climate change scenarios is being issued.

We established the policy tipping points for various water management issues, including coastal protection and flood defense, and distinguishing between policy strategies and individual measures (Passchier et al. 2009; Kwadijk et al. 2010). This revealed that the present policy *strategy* can be continued for at least this century and probably several centuries to go, as long as the sea level rise does not exceed 1.5 m per century. This applies to the coastal protection strategy of sand nourishment from >20 m depth onto the foreshore, as well as to the flood defense strategy of regularly raising the embankments along the major estuaries and lakes, and to the room-for-rivers strategy adopted for the major rivers, which aims at enlarging the discharge capacity with increasing design discharges.

As for individual *measures*, the first major replacement is expected to be that of the Maeslant storm surge barrier, which protects Rotterdam. This is due between 2060 at the earliest and 2200 at the latest, depending on the climate scenario and on whether its flood defense function or its technical lifespan becomes the limiting factor. The barrier was designed for a sea level rise of maximum 0.5 m, but it may be topped up a bit. Too frequent closure, however, could compromise the designed lifespan of the hinges—which relates to the number of closures—and the yearly maintenance—which requires the temporary deployment of the barrier (Passchier et al. 2009). Too frequent closure is also feared by Rotterdam Harbor, as it hinders shipping. Whatever decision on this storm surge barrier is made, the present construction cannot prevent the rise of the 1:10 000 design water levels inshore of the storm surge barrier, because of its own failure probability of about 1: 100 per closure request. The inshore design water levels therefore follow the sea level rise by more than 90%.

A second major decision is required on the water level management of Lake IJssel. The level of this huge freshwater lake is maintained within narrow boundaries in view of reducing flood risk (keep it low, especially in winter: −0.4 m NAP (Netherlands' reference water level, about mean sea level)) and freshwater supply (keep some storage, especially in summer: −0.2 m NAP) by discharge sluices. Even with the planned enlargement of the sluices, the water levels cannot be maintained within these boundaries from about 2050 at the earliest. Before then, a decision must be made on whether to start pumping or to follow the sea level rise.

We have thus established that the present Netherlands' flood risk management strategy relies primarily on flood protection. That it is essentially adaptive by its legal and regulatory definition. And that it can be sustained for centuries to come in view of the now-expected climate change and sea level rise rates, but not without implementing some major improvements to the flood defense and water management structures.

DEVELOPMENT OF FLOOD RISK

The above may suggest that the Netherlands does not have to worry about sea level rise or an increasing flood risk. Such a conclusion is, however, premature. We analyzed the development of both economic flood risk and fatality risk in the Netherlands, by establishing how the various determinants of flood risk develop, i.e., not only climate, but also society.

Flood risk can be defined as probability multiplied by consequence or as a function of a flood hazard's probability and exposure characteristics and the vulnerability of the exposed socio-economic system (Klijn et al. 2004b; Samuels et al. 2006; FLOODsite 2009). This requires that we not only analyze the expected future development of hazard and flooding probabilities, but also that of exposure characteristics and of the vulnerability of the people and their property and economy. Because socio-economic development is much more uncertain than climate change, and it is generally believed that scenarios cannot be extended beyond a few decades from now, we limited this analysis to 2050. This means that all figures below relate to 2050, in contrast to those in the previous sections, which relate to 2100.

With the scenarios on sea level rise and design river discharge, we first analyzed the increase in *hazard probabilities* (Klijn et al. 2004b). The expected rise of design water levels differs along the rivers, the coast, in the estuaries where the two meet, and on Lake IJssel. The sea level in 2050 may have risen between 15 and 45 cm, which corresponds with an increased exceedance probability of the design water level with a factor of about 2–3. The 1:10 000 per year flood would then have become a 1:5000 or 1:3000 per year flood. The same factor was found to apply for the estuaries and downstream river stretches. The design water level of Lake IJssel is not expected to rise before 2050, because larger discharge sluices are being built. For the upstream stretches of the large rivers, the design discharge in 2050 may reach 17 000 $m^3 s^{-1}$ in the wettest scenario, in comparison to the present 16 000 $m^3 s^{-1}$. This translates into design flood levels that are about 0.1- 0.2 m higher than those which apply now, depending on the river branch and precise location. These correspond with an exceedance probability of the design flood level that is almost twice as large.

These increases in hazard probability would correspond with increases in *flooding probability*, if we would presume no further raising of the embankments or other counteracting measures. However, we already ascertained that the Netherlands' flood defense policy is adaptive and calls for action in response to any increase of hazard probability. More importantly, many flood defense measures have already been decided on for those places where a backlog has been established in complying with the current protection standards. Their implementation is underway, for example for the weak spots along the coast (practically finished), for the re-enforcement of various embankments which were found inadequate (Flood Defense Program, until 2013), and by making room for rivers (Room-for-River Program, until 2015). This implies that, firstly, the current flooding probabilities are larger than they should be—although smaller than ever before in the last 50 years—and that, secondly, the actual flooding probabilities will even further decrease until about 2015, in contrast to what one might expect. From 2015 onwards, the flooding probabilities may be expected not to rise but to stay constant.

A larger difference between water level—in river or sea—and land level in the protected areas may have consequences for the *exposure* when a flood defense fails. Greater water depths may be attained and/or greater surface areas may be flooded. This issue was investigated by performing a number of flooding simulations for selected dike-ring areas which we considered representative for certain flood risk situations along the coast (compartmentalized dike-rings in the coastal plain, deep 'bathtub' polders, etc.). The flooding simulations were done for the present sea level and for a 1.3 m raised sea level (Figs. 2, 3), assuming breaches at the same locations and at the highest flood level, after which the breaches were allowed to develop unhindered. The simulations were done with the Sobek 1D/2D model, which is well validated (Hesselink et al. 2003), applying very accurate elevation data obtained by laser altimetry (Actual Elevation database Netherlands, AHN), with less than 0.1 m vertical errors. For the reliability of the simulations the 1D-element in the model is even more important, as it not only takes into account linear obstacles, but also preferential water flow along canals and ditches. Next the resulting economic damage and number of fatalities were calculated for the present land use and population in order to establish the separate contribution of greater exposure to risk increases.

The simulations for the coast showed that at higher sea levels the breaches grow much larger and inflow volumes may double. The area which is flooded increases (Figs. 2, 3), and so do the water depths. Economic damages along the coast increase with a factor of 2.2 to 3.7 for different breach locations and fatality numbers with a factor from 3.1 to 4.7. These results were extrapolated to the remainder of the coastal dike-ring areas by expert reasoning taking into account their location, size, degree of compartmentalization, land-use characteristics and population distribution. As the factors thus found apply for a 1.3 m higher sea level, figures for lower sea level rises were derived by linear interpolation.

Similar—but simpler—calculations were done for Lake IJssel, which has a fixed volume in contrast to the endless ocean; here a breach in an embankment surrounding a deep polder thus results in an equilibrium water level in 'communicating vessels'. Along the rivers, the dike-rings are inclined and already may fill up onto the lowest level of the surrounding embankments, whereas the room-for-river policy prevents a further rise of the water level in the rivers. The exposure here will hence not change.

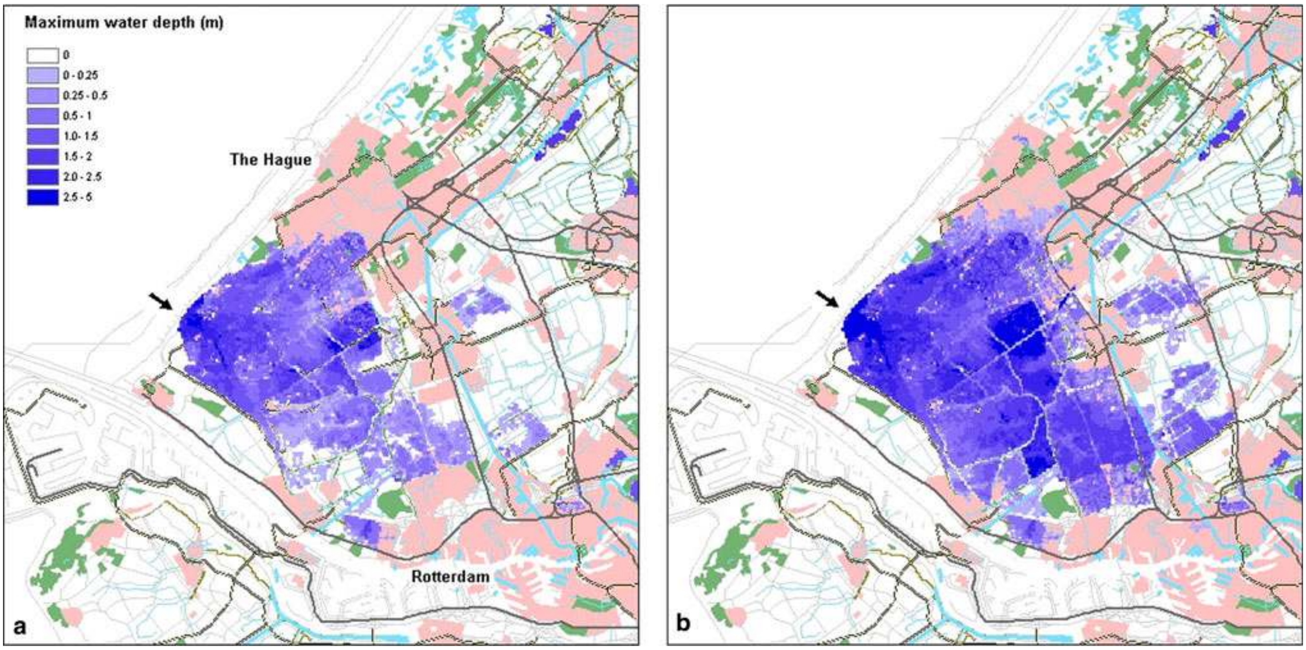

Fig. 2 Difference in exposure in terms of flooded area and water depth resulting from a breach at Ter Heijde (indicated with an *arrow*) during a 1:10 000 storm surge level with present sea level (**a**) and with a sea level that is 1.3 m higher (**b**)

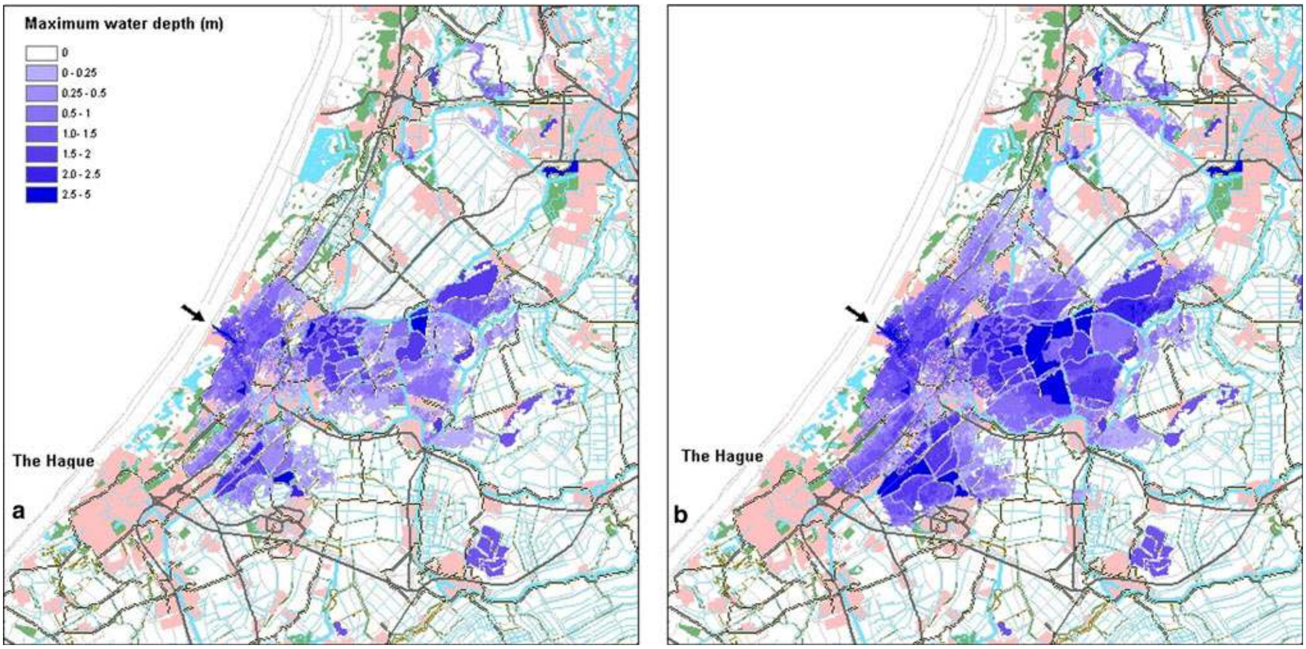

Fig. 3 Difference in exposure in terms of flooded area and water depth resulting from a breach at Katwijk (indicated with an *arrow*) during a 1:10 000 storm surge level with present sea level (**a**) and with a sea level that is 1.3 m higher (**b**)

Summarizing for the sea level rises expected in the scenarios of KNMI, we derived a contribution of increased exposure on economic flood risk for 2050 of factor 1.7 at the maximum for some coastal dike-ring areas.

A final risk component is the socio-economic *vulnerability*. This divides into people, as a function of demography, and potential economic damage, as a function of economic value and economic activity. The future development of the

Netherlands' population and economy is also represented by four scenarios drafted by the joint National Planning Agencies (Table 2) and translated into land use maps (Koomen and Van der Hoeven 2008). The scenarios apply for 2040 and show demographic changes varying from a shrinkage to 15.8 million inhabitants ('Regional Communities': RC) to a growth to 19.7 million (Global Economy': GE), from the present 16.0 million. The yearly economic GBP growth in these scenarios ranges from 1.2% per head (RC) to 2.1% per head (GE).

For two of the four scenarios (GE and 'Transatlantic Markets': TM; Table 2) the figures were translated into land use maps and—taking into account the present stagnation because of the recent economic crisis—were considered 'a fair estimate' of possible land use scenarios in 2050. In this exercise, part of the economic growth was attributed to new urban development and part to increasing value of property. New urban development relates to population increase and the reduction of household size. Thus, we obtained two possible future land-use maps (one of which is shown in Figure 4 in comparison to present land use) as well as an estimate of the additional growth of economic damage potential.

It was found that the vulnerability in the flood-prone part of the country increases above the country's average. The potential loss-of-life increases above average through a significantly larger population growth in the western part of the country, between the Rhine River branches in the center of the country, and in some polders around Lake IJssel. People tend to move toward these areas which offer the largest economic and job perspectives. The potential economic damage increases by 2050 with 22% through new urban development, augmented with 74% through other economic growth in scenario Transatlantic Markets, and by, respectively, 45% plus 89% in scenario Global Economy. These figures for the whole country are supported by local and regional analyses with comparable results (Maaskant et al. 2009; Botzen et al. 2010; Bouwer et al. 2010). They mean that the flood risk could increase with a factor 2.0 to 2.3 as a consequence of demographic and economic growth alone. These factors overwhelm the effect of increased exposure due to rising sea levels.

A COMPREHENSIVE FLOOD RISK ASSESSMENT

With the above established developments in flood probability, exposure and vulnerability, we quantified the fatality risk and the economic risk in each dike-ring area and added them up to arrive at figures for the country as a whole. We did so for three moments in time: for the current situation (applying precise data on land use and population from about 2000–2005 and subsequent minor adjustment to achieve figures for 2009), for the situation in about 2020 when all flood defense and control measures are expected to be in force, and for 2050. For this last moment, we distinguished between two socio-economic scenarios, because these cause the largest differences in total flood risk. Compared to demographic and economic growth the contribution of increased exposure due to higher water levels is small and geographically confined to the coastal areas, whereas increased flood probabilities are not to be expected under the present legal and regulatory arrangement.

Figures 5 and 7 show that the currently implemented flood defense and control measures cause the fatality risk and the economic risk to decrease by a factor of more than 3.0 and about 2.5, respectively. The difference is caused by a low population growth between 2009 and 2020, whereas economy is supposed to grow steadily. Between 2020 and 2050 flood risks increase again; fatality risk only slightly in scenario Transatlantic Market—with about 2%—, but significantly in Global Economy—with some 20%. Economic risk increases faster, proportionally to the different economic growth rates in the two scenarios; with some 40% in Transatlantic Market and with more than 70% in Global Economy.

Table 2 Four socio-economic scenarios for 2040

	1971–2001	RC 2040	TM 2040	SE 2040	GE 2040
Population size (millions)	16.0*	15.8	17.1	18.9	19.7
Share age 65+ (%)	14*	25	25	23	23
Number of households (million)	7.0*	6.9	8.5	8.3	9.8
Unemployed job-seekers (%)	3.3	7.7	4.7	5.5	4.3
Growth of GDP per head per year (%) 2002–2040	1.9	1.2	1.7	1.5	2.1
GDP per head (2001 = 100)	100*	133	195	156	221
Claims on space for living and working (2002 = 100)	100#	13	76	75	139
Claims on space for recreational and natural area (2002 = 100)	100#	128	112	163	156

* Index 2001 = 100

\# Index 2002 = 100

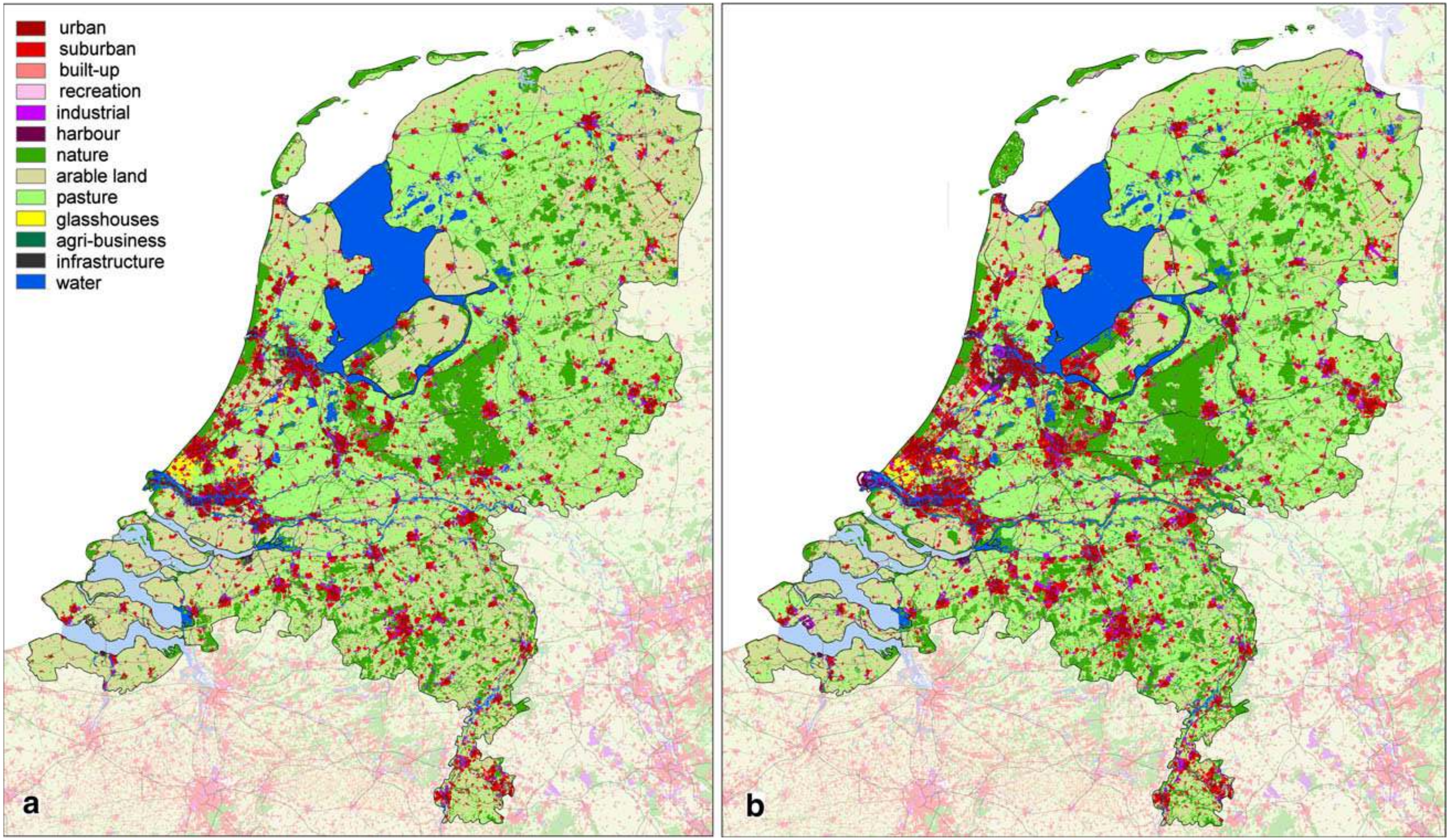

Fig. 4 Land use in the present situation (**a**) and possible land use in 2050 in scenario Transatlantic Market (**b**; after Kuiper and Bouwman, 2009)

Figure 6 shows the positive effects on fatality risk of implementing the present flood defense and control measures that are reflected by a more even distribution of risk over the country in 2050 (b) in comparison to the present situation (a). This can largely be attributed to the room-for-rivers policy which effectively reduces the flood probability along the Rhine and Meuse Rivers, and for a small part to improvements to the flood defenses. But another significant part of the explanation lies in the relatively high fraction of people assumed to be evacuated from dike-ring areas along the rivers, which outweighs the higher flooding probability along the rivers. The fact that river floods can be forecasted days ahead of their arrival allows timely and hence effective evacuation.

If we look at Fig. 8, we see that the economic risk in 2050 is not so evenly distributed over the country. Property cannot evacuate when a flood is immanent. The economic risk along the rivers is relatively high, due to relatively large flooding probabilities but even more because of the fact that these dike-ring areas are usually being flooded completely and to great depths, in contrast to compartmentalized coastal areas. This insight was gained from flooding simulations, which showed that breaches tend to result in very prolonged inflow of water (much longer than at the coast during a storm surge), throughflow to the lower end, and sometimes even domino-effects of next-in-line dike-ring areas being flooded. This is reflected in Fig. 8 by dark shades along the rivers, also in the future. Moreover, we find some dangerously large dike-ring areas which might benefit from compartmentalization. And especially in those dike-ring areas the economic development is above average because of recent improvements to the infrastructure (new railroads and highways), which attracts human activity and investments.

DISCUSSION

The comprehensive flood risk assessment, which we performed, was the first to fully—though roughly—assess the influence of the different constituents of risk for the whole country. Much research has been and is being performed on either individual constituents of risk, for example flood probabilities or potential consequences, or on parts of the country only. But only by a comprehensive flood risk assessment which takes into account all the constituents of risk in combination, for all the Netherlands' dike-ring areas and for various moments in time, we can gain new insights on flood risk proper, which is—after all—what is needed for sound flood risk management policy making.

Before going into our main findings and their implications for future flood risk management, we need to emphasize that our results should be considered in the context of the obvious limitations of the approach. These concern the risk calculations and the future outlook.

As for the risk calculations, we have applied the best available knowledge and data on many risk constituents, but because we also needed full coverage of the whole country we were obliged to extrapolate, interpolate and make a number of assumptions. These of course affect the reliability of the outcomes. From more detailed studies (Klijn et al. 2010b), we learned that risk calculations for dike-ring areas are particularly sensitive to uncertainty in the flood probability estimates, and that flood probability is also the most difficult to establish risk constituent. We tackled this, as explained in "Development of Flood Risk" section, by assuming that in the near future the embankments comply with the design standards, although we know they did not in the past, and by assuming that overtopping is the only relevant failure mechanism to take into account. By applying these same assumptions for each scenario, we at least achieved comparable results. But we need to emphasize that the absolute risk figures we present in Figs. 5, 6, 7, and 8 may be wrong by—grossly estimated—a factor of two for economic damage and even more for fatality risk, and should therefore be interpreted with care. The relative differences between the scenarios, as shown in Figs. 5 and 7, still allow, to our opinion, to draw relevant conclusions.

As for the look into the future, we are confronted with uncertainties of a kind that cannot be reduced by more research. These would probably classify as 'deep uncertainty' according to the classification of Kwakkel et al. (2010). One of the few possible approaches in such a case is asking 'What, if…?', and one of the few generally accepted methods is to apply a range of scenarios (Evans

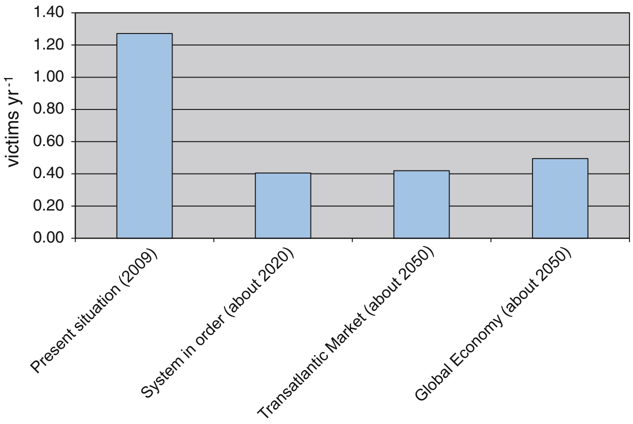

Fig. 5 Indicative change of fatality risk (mean number of victims per year) between present and 'system in order' (about 2020) and increase of fatality risk in two socio-economic (demographic) scenarios

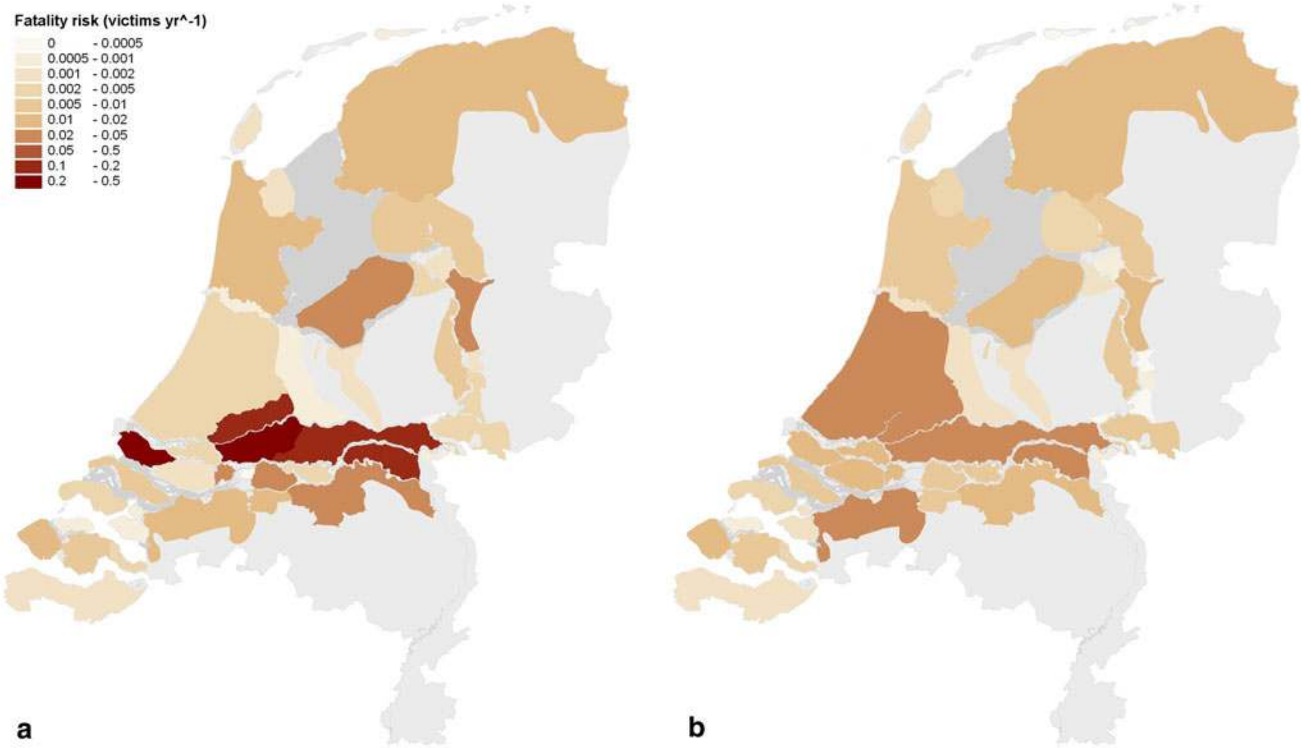

Fig. 6 Geographic distribution of fatality risk over the Netherlands, as a function of flood probability and consequence, in the present situation (about 2009; **a**) and the future situation (about 2050) assuming socio-economic scenario Transatlantic Market and current policy (**b**)

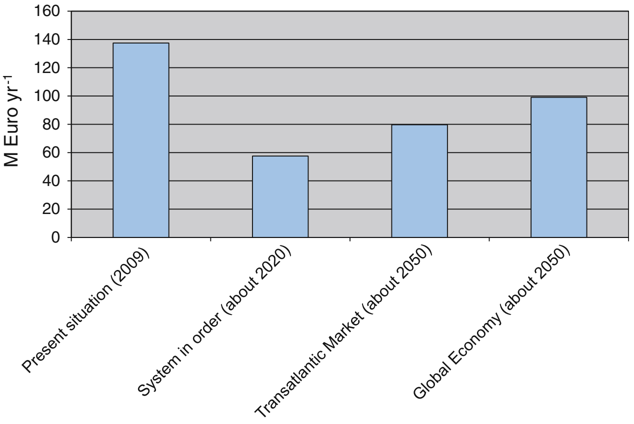

Fig. 7 Indicative change of the economic damage risk (mean yearly damage in million Euros) and the influence of two different economic growth scenarios on economic damage risk, distinguishing between value increase and new development

et al. 2004; De Bruijn et al. 2008a; Haasnoot et al. 2009). In this article, we only considered one climate scenario and two socio-economic scenarios, as we were in search of the relative contribution of each to the development of flood risk in the next few decades when the climate scenarios do not diverge much yet. This too means that the absolute figures, which we present in Figs. 5 and 7, should be considered as indicative only: economic risk or fatality risk in the future may be higher or lower, or alternatively the moment the calculated risks are being 'realized' may lie earlier or later in the future.

Despite these limitations of our approach, we feel that the trends and relative contributions of flood probability, exposure and vulnerability we discovered are relevant for the debate on future flood risk management policies.

Firstly, it was found that climate change and sea level rise do indeed cause the flood hazard to increase, as shown in the "The Present Netherlands' Flood Risk Management Policy: Tipping Points" section, and call for adaptation. And it was ascertained that exposure is likely to increase, through greater flooding depths (Figs. 2, 3). But is was also established in this same section that even the low-lying Netherlands can be protected against these effects quite easily for many decades to go and even centuries with the current technology and even without any major change of flood risk management strategy. More precisely, the current Netherlands' flood risk management strategy is already adaptive.

Secondly, in the "Development of Flood Risk" section, we found that socio-economic development poses at least as big a challenge for flood risk management as climate change does. For the Netherlands especially economic

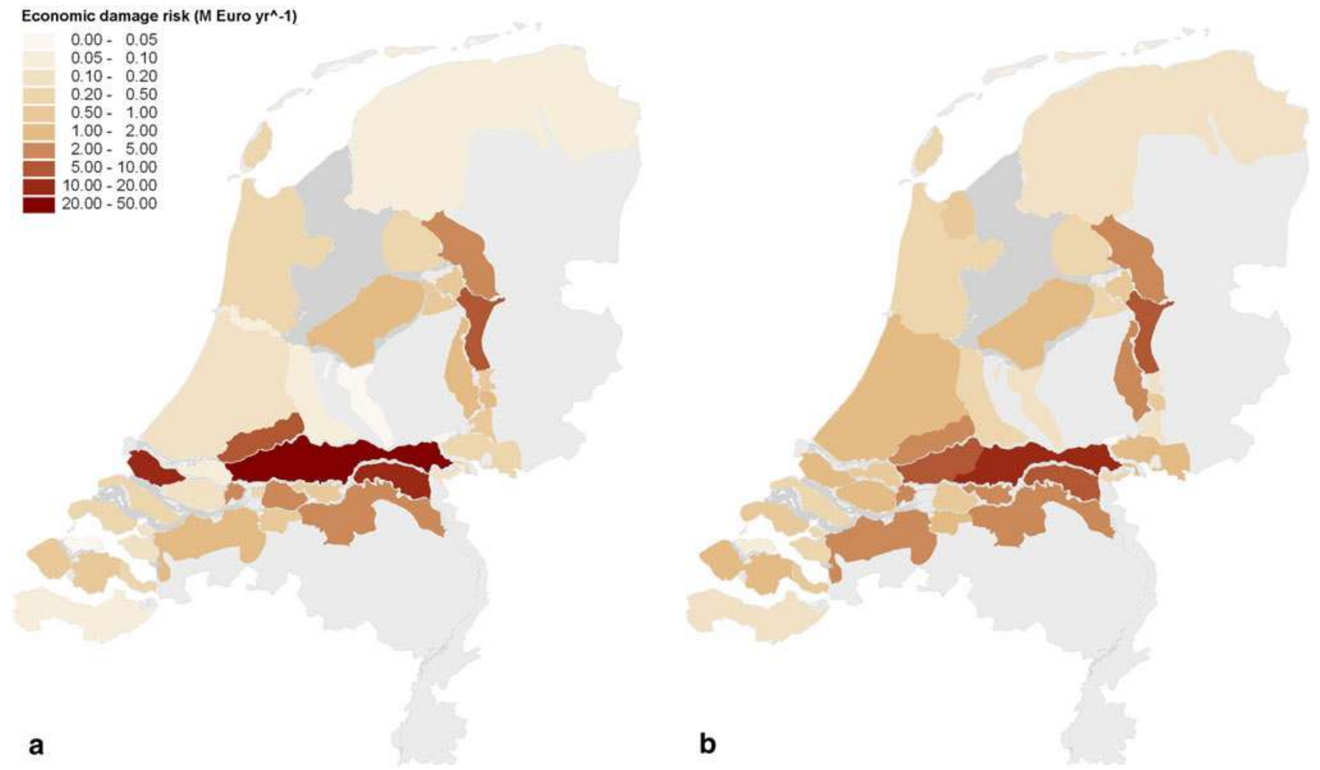

Fig. 8 Geographic distribution of economic risk over the Netherlands, as a function of flood probability and consequence, in the present situation (about 2009; **a**) and in the future situation (about 2050) assuming socio-economic scenario Transatlantic Market and current policy (**b**)

development causes the economic flood risk to increase, and as fast as climate change might do, even at growth rates of only about 2%. This increasing vulnerability alone already calls for updating the flood risk management policy, even without climate change. Fatality risk in the Netherlands increases relatively slow, because the population does not grow much any more. But we do see the population's centre of gravity move toward the flood-prone parts of the country, which calls for extra attention. Fatality risk may, however, especially require attention in other deltas of the world (Nile, Mekong).

Thirdly, our analyses revealed an uneven distribution of both fatality flood risk and economic flood risk (Figs. 6, 8). This uneven distribution is very obvious in the current situation and will become somewhat less in the near future as a consequence of the measures already planned. But even in the future, the economic risk distribution over the country remains uneven. This may call for either better flood protection, or dedicated spatial planning.

This brings us to the disadvantages of the present flood risk management policy. This policy is essentially a policy of flood defense only. It originates from reacting on flood disasters in the past, but evolved toward a risk-based flood defense policy with the calculations of the Delta Committee in the 1960s. Since that committee, however, the increasing societal vulnerability has not been taken into account, and has certainly not been anticipated on. Now that this increased and further increasing societal vulnerability is being recognized, as well as the lack of relationship between protection level and risk (Ten Brinke and Bannink 2005, based on the results of Klijn et al. 2004b), the policy response is again one of improving the flood defense, as some recent developments show. For recently, the government has begun to revise the Netherlands' flood risk management strategy, in response to debate about the report by Ten Brinke and Bannink (2005) and also in response to the advice of the 2nd Delta Committee (2008), which advised on adaptive water management in view of climate change.

The future strategy as proposed by the government is characterized by a three-layered approach: (1) flood defense, supplemented by (2) sustainable spatial development, and by (3) disaster management. In the context of a revision of the first layer, the adequacy of the current protection levels is now being thoroughly investigated and proposals for updating these levels are being debated. The revision of the protection levels is likely to be based on cost–benefit analyses (Jonkman et al. 2004; Eijgenraam 2006), and on assessments of local individual risk and group risk—or collective risk (De Bruijn et al. 2008b).

Obviously, this approach still gives preference to flood defense, as it considers the second and third layer as supplementary and not as obligatory. More specifically, in the analyses the development of the socio-economic vulnerability in the future is considered as a given, and not as something which might be influenced by dedicated policy. This affects the outcomes of the cost-benefit analyses and hence of the resulting optimal protection levels. These might be lower, when the exposure or vulnerability could be decreased by compartmentalization (Klijn et al. 2010b), by spatial planning, or by other measures.

Secondly, raising the protection standards does not prevent dike breaches and flooding events in places where large numbers of fatalities (De Bruijn and Klijn 2009) or huge economic consequences are expected. Such events might classify as disasters because the impacts are beyond control. We could imagine alternative flood risk management measures or strategies that primarily aim at preventing such uncontrollable disasters to happen. The current policy strategy is not suited for this.

Thirdly, as the proposed policy strategy does not prevent the gradual increase of the vulnerability in the flood-prone parts of the country, the country's vulnerability as a whole will remain to increase. Whether this is desirable—and sustainable in the long run—is not questioned. In the present practice, sustainable spatial development is only pursued in active floodplain areas, but not within protected areas yet. And in the proposed strategy it is only considered as supplementary to flood defense.

To our opinion, these disadvantages of the present and of the proposed new flood risk management strategy at least call for comparisons with alternative flood risk management strategies in order to establish which is the most desirable and whether some of the flaws we recognized can be reduced. We already performed some preliminary exercises of this kind (Klijn et al. 2007, 2010a), the results of which provoke lively debate within the research and policy-making communities.

Acknowledgments The writing of this article was subsidized by the Netherlands' research program Knowledge for Climate (Theme 1: Climate-proof Flood Risk Management) and is partly based on research within the Integrated Project FLOODsite (EU-6th Framework Programme, Contract GOCE-CT-2004-505420).

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AUTHOR BIOGRAPHIES

Frans Klijn (✉) is a senior specialist in Delta Technology, working at Deltares (The Netherlands) since 1996. Trained as a physical geographer and landscape ecologist, he has been working on River Basin and Coastal Zone Management since 1980. In 1990s, he played an important role in the societal debate on the management of the Netherlands' large rivers, which culminated in the Room-for-Rivers policy. Presently, he co-ordinates the research on climate-proof flood risk management of the Netherlands' Knowledge for Climate Program.

Address: Deltares, PO Box 177, 2600 MH Delft, The Netherlands.
e-mail: frans.klijn@deltares.nl

Karin M. de Bruijn is a senior researcher in Flood Risk Management, working at Deltares since 1998. Trained as a hydrologist, she has been working on flood inundation modeling, flood risk analysis and assessment, and the development and assessment of long-term flood risk management strategies in an uncertain future. She is especially known for her work on resilience of flood risk systems.

Address: Deltares, PO Box 177, 2600 MH Delft, The Netherlands.
e-mail: karin.debruijn@deltares.nl

Joost Knoop is a senior researcher at the Netherlands' Environmental Assessment Agency since 2000. Trained as a chemical engineer (Twente University) he has been head of the Department of Mathematical Models and Statistics of the Water and Drinking Water Unit of the National Institute for Public Health and the Environment for many years. Since his return to research, he is mainly involved in policy studies on the adaptation to climate change in the field of water.

Address: PBL Netherlands' Environmental Assessment Agency, PO Box 303, 3720 AH Bilthoven, The Netherlands.
e-mail: joost.knoop@pbl.nl

Jaap Kwadijk is a Director of Research of the section Inland Water Systems at Deltares, after a career as researcher in the field of hydrology, climate change impact assessment and flood forecasting. In 1990s, he played a key role in the climate change impact assessment studies for the river basins of the Rhine and Meuse. He co-ordinated the EU-funded development of a medium range Flood Early Warning System for the whole of Europe.

Address: Deltares, PO Box 177, 2600 MH Delft, The Netherlands.
e-mail: jaap.kwadijk@deltares.nl