Global Environmental Change 21 (2011) 1045–1060

Contents lists available at ScienceDirect

Global Environmental Change

journal homepage: www.elsevier.com/locate/gloenvcha

Climate change impacts on pricing long-term flood insurance: A comprehensive study for the Netherlands

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ARTICLE INFO

Article history:
Received 3 November 2010
Received in revised form 17 March 2011
Accepted 12 April 2011
Available online 28 May 2011

Keywords:
Adaptation
Climate change
Flood risk
Long-term insurance
Uncertainty
The Netherlands

ABSTRACT

Recently long-term flood insurance contracts with a duration of 5, 10 or 15 years have been proposed as a solution for covering flood risk and mitigating increasing flood losses. Establishing a long-term relation between the policyholder and the insurer can provide better incentives to reduce risk through undertaking damage mitigation measures. However, the uncertainty about the development of future flood risk in the face of climate and socio-economic change may complicate insurers' rate-setting of long-term contracts. This issue has been examined in this study by estimating the effects of these changes on flood risk and pricing flood insurance premiums of short- and long-term flood insurance contracts in all (53) dike-ring areas in the Netherlands. A broad range of simulations with hydrological and flood damage models are used to estimate the future development of flood risk and premiums. In addition, the long-term development of insurance funds is estimated with a spatial "Climate Risk Insurance Model (CRIM)" for a private insurance arrangement and for a 'three-layered' public-private insurance program. The estimation of flood insurance premiums of long-term insurance contracts reveals fundamental problems. One is that there is an incentive for either the consumer or the insurer to prefer short-term rather than long-term contracts in the face of climate-related uncertainty. Therefore, it seems advisable to examine the introduction of one-year flood insurance contracts in the Netherlands, at least until the large uncertainties with climate and socio-economic change on flood risk have been resolved. The estimations performed with the Climate Risk Insurance Model indicate that a private insurance fund could have difficulties with building up enough financial reserves to pay for flood damage, while the layered public–private insurance scheme is more robust.

1. Introduction

Economic and insured losses caused by floods have increased considerably during recent decades due to socio-economic developments. These losses are mainly caused by an increased concentration of economic values and population in vulnerable areas, such as coastal zones and floodplains (Bouwer et al., 2007; Munich RE, 2008). Flood losses are expected to increase in the future as a result of the continuation of urbanization in vulnerable areas – particularly in coastal areas. In addition, climate change is projected to exacerbate flood risk through sea-level rise and an increase of extreme precipitation (IPCC, 2007; Aerts et al., 2009).

When focusing on flood risks in the Netherlands, different flood management strategies can be followed to limit the increase in flood losses. Since the major flood disaster in 1953 that caused about 1800 casualties, the flood management strategy followed by the Dutch government aims solely at developing measures that lower the probability of the flood hazard. In addition, it has been realized that a more comprehensive strategy is required to cope with climate change, given the particular vulnerability of the Netherlands to flooding, which could comprise improved evacuation planning, introducing financial risk-sharing arrangements, as well as implementing damage mitigation measures (Aerts et al., 2008a; Botzen and van den Bergh, 2009). Private flood insurance is currently not available in the Netherlands. The only financial arrangement in place is an ex post disaster relief arrangement established in 1998, which provides partly compensation by the government through the Calamities and Compensation Act (WTS) (de Vries, 1998). In 2003 a small flood event in Wilnis caused damage of about €16 million of which about half was compensated through the WTS, while currently in 2011 court cases are still ongoing about the compensation (not) provided. The WTS has several disadvantages and is, for example, undesirable from a social welfare perspective because the political decision to compensate losses is not based on well-defined criteria. As a consequence, households face uncertainty about whether, and how much, flood damage will be compensated. Moreover, the WTS is an ad hoc arrangement for which no reserves have been

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doi:10.1016/j.gloenvcha.2011.04.005

established. Another drawback of the scheme is that it does not provide incentives to households to take measures that would minimize damage, such as elevation or flood-adapted interior fitting (e.g. Priest, 1996).

On the basis of the shortcomings of the current compensation arrangement and the projected increase in risk due to climate change, there have been discussions between the government and insurance companies about introducing a new flood insurance system (Jongejan and Barrieu, 2008). This is in line with the intention of the government to transfer responsibility of natural disaster compensation to the private market where this is possible (Kok, 2005; Adviescommissie and Water., 2006). Botzen and van den Bergh (2008) show that a pure private flood insurance in the Netherlands is complicated by accumulating risks, low capacity of insurers to pay for catastrophic damage, and problems with asymmetric information, among other issues. They propose establishing a public-private 'three-layered' flood insurance system in the Netherlands, as has been proposed for insuring natural catastrophe risks in other countries, such as the USA (Kunreuther, 2006a; Kunreuther, 2006b).[1] In this three-layered program, a first layer of small losses is paid by households through deductibles in insurance contracts. In the second layer of the insurance program, private insurance companies cover larger losses using risk-based premiums. The government covers a third layer of very large losses to prevent problems with the insurability of highly correlated risks, and the limited financial capacity of the Dutch insurance sector. A certain maximum amount of damage defined as a 'cap' could be specified that will be paid by the insurance sector, while the government will compensate the remaining damage if actual flood damage exceeds this cap. It has been suggested by insurers that this cap would be in the order of between €1 billion and €5 billion, although further research needs to confirm this (Aerts, 2009). An important issue that has not been studied so far is how to design such a layered insurance scheme that is capable of coping with future trends and increasing flood risks, and also encourages policyholders to undertake cost-effective damage mitigation measures (Kunreuther, 1996; Kleindorfer and Kunreuther, 1999; Botzen et al., 2009).

Recent studies advocate the use of long-term flood insurance contracts on residential properties to provide financial security for homeowners and stimulate investments in risk reduction (Kunreuther, 2008; Jaffee et al., 2008; Kunreuther et al., 2009). Long-term insurance contracts, e.g. with a duration of 5, 10, or 15 years, have several advantages over short-term insurance policies. Long-term insurance contracts decrease transaction or search costs to consumers in case annual policies are not renewed by their insurer. Similarly, long-term contracts reduce the administrative costs of insurers as consumers commonly cancel their (short-term) policies, as has been witnessed in the USA, if households had not experienced a flood for a few years (Michel-Kerjan and Kousky, 2010). Another advantage for consumers is that future premiums are specified in the contract, so that no unexpected large premium increases can occur after a natural disaster as, for example, occurred after severe hurricanes in Florida.

Moreover, long-term insurance could be more effective in promoting damage mitigation than short-term insurance contracts. Homeowners may be reluctant to undertake mitigation when they have short-term insurance contracts, because of uncertainty about both whether they will stay in the same house in the future and whether the insurer will charge lower premiums that reflect reduced risk for a long time period. A long-term insurance contract can be tied to the property instead of the individual, and provide benefits for the insured, such as premium discounts, for the entire duration of the contract if individuals invest in risk-reducing measures. With such a contract, investments in mitigation may be financed with mortgage loans, which spread the upfront investment costs for individuals over time. Undertaking a cost-effective mitigation measure would then reduce yearly insurance premiums by more than the yearly increase in mortgage payments used to finance the investments, which benefits consumers.[2] Insurance companies and banks that offer the mortgage also benefit since the vulnerability of the property to natural hazards has been reduced, so that a win-win situation can be created for all involved parties (Kunreuther et al., 2009).

A problem with long-term flood insurance contracts is that it is difficult to set accurate risk-based premiums because of the inherent uncertainty of future risks that are influenced by uncertainty about the effects of climate change on flood risk and by projections of socio-economic developments that influence future flood damage (IPCC, 2007). This uncertainty may hamper the development of long-term insurance markets in two main ways. It can be expected that insurance companies will account for this uncertainty in the pricing of risk, and charge premiums that are considerably above actuarially fair levels (e.g. Kunreuther et al., 1995). Or, insurance companies may be unwilling to offer long-term insurance products if they have insufficient insights into future risks and corresponding risk-based premiums, and prefer the flexibility of short-term contracts that can be cancelled or adjusted after 1 year. Therefore, it is imperative to obtain insights into the potential effects of climate and socio-economic change on future flood risk and flood insurance premiums, and into the feasibility of setting adequate premiums of long-term contracts. This has not been studied so far.

In this study, we focus on exploring the future development of long-term flood insurance premiums in the Netherlands under a range of socio-economic and climate-change scenarios. The objective is to obtain insights into the development of risk-based premiums over a long time horizon. This is done by estimating flood risks and premiums over time using different representative scenarios of sea-level rise in combination with socio-economic scenarios on population and economic growth. Flood risks and flood insurance premiums for the Netherlands are spatially assessed by estimating future premiums for 53 geographically low-lying dike-ring areas. This is done by means of a broad range of simulations with hydrological and flood damage models for the Netherlands. On the basis of these results, the feasibility of introducing flood insurance is examined by estimating the dynamics of insurers' funds in the face of several flood scenarios. A "Climate Risk Insurance Model (CRIM)" has been developed to test the feasibility of both a private insurance market and a layered insurance program described by Botzen and van den Bergh (2008). The results can aid policymakers and insurers in the Netherlands who are considering introducing flood insurance. Moreover, the results provide useful insights into the uncertainties associated with setting long-term insurance premiums, and contribute to the emerging literature on this topic.

The remainder of this paper is structured as follows. Section 2 outlines the insurance model and data used in the analysis. Section 3 examines the development of risk-based premiums under a

[1] A fully public insurance paid out of taxes may be less efficient because raising taxes is costly and is associated with distorting effects on markets, and establishing a new public insurer is likely to be more expensive than making use of the already existing insurance sector. We note that high surcharges on insurance premiums that are sometimes observed in fully private insurance systems can be overcome in the public-private insurance arrangement, because the government provides reinsurance at low actuarially fair costs.

[2] This is the case because the costs of undertaking mitigation, which are the yearly interest and repayments of the mortgage, are lower than the yearly reduced damage that is reflected in lower yearly risk-based premiums when measures are cost-effective.

range of socio-economic and climate- change scenarios. Section 4 discusses the results of the insurance feasibility model for a private flood insurance market and a layered program. Section 5 concludes.

2. Methods

The lower-lying part of the Netherlands is divided into 53 dike-ring areas that have their own flood protection system, as Fig. 1 shows. A dike-ring is a separate administrative unit under the Water Embankment Act of 1995. This act aims to guarantee a certain level of protection against flood risk within each dike-ring area. For example, a dike-ring with a safety standard of 1/10,000 has been designed in such a way that it is built high enough to withstand a flood with a probability ('return period') of 1 in 10,000 years. The safety standards of dike-rings vary between 1/10,000 and 1/1,250 throughout the country (Fig. 1). These safety standards do not consider future climate change.

The actual rise in sea level and increase in maximum river discharge that will materialize in 2040 and 2100 is uncertain (IPCC, 2007). In addition, the socio-economic projections that influence future flood risk are uncertain. Therefore, it seems advisable to explore the potential effects of climate change on flood risk by generating simulations of both flood probability and potential damage, using a broad range of climate and land use projections. This enables for obtaining insights into the relative differences of climate change effects on flood risks by using these scenarios, and examining to what extent flood

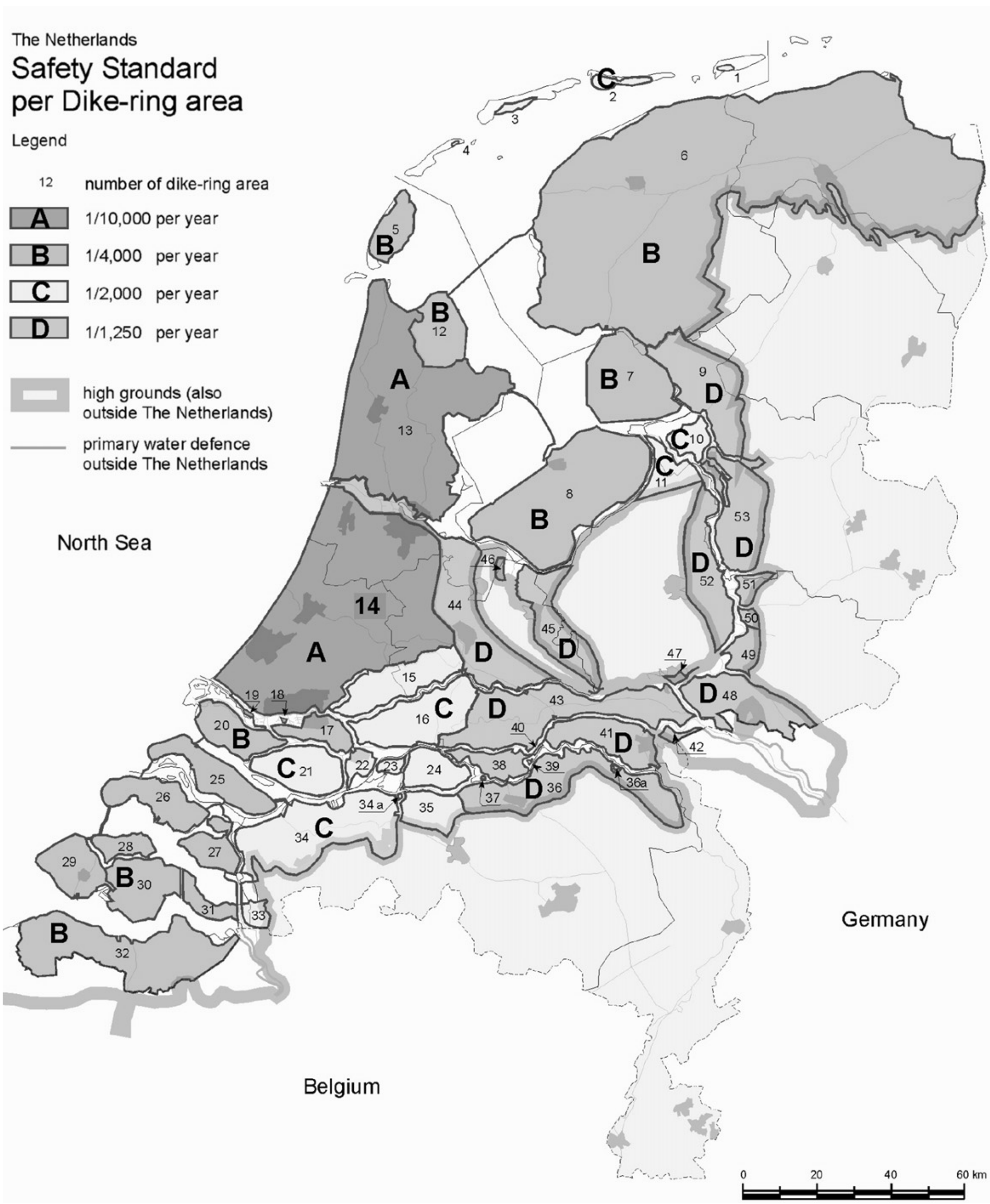

Fig. 1. Safety standards of dike-ring areas in the Netherlands.

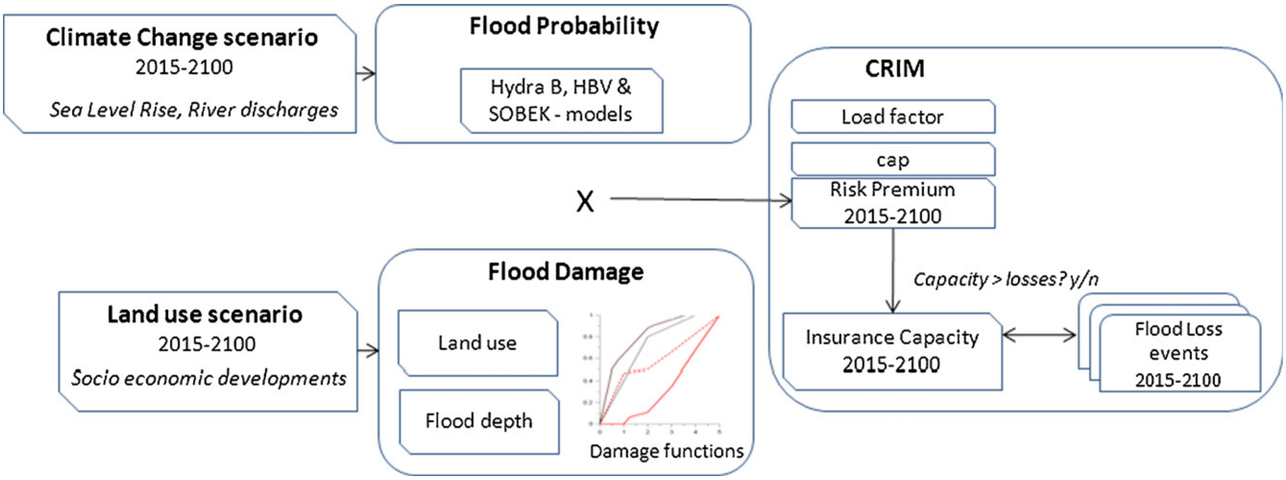

Fig. 2. Schematic overview of the approach to calculate current and future flood risk for each of the 53 dike-ring areas. The risk simulations are used in a Climate Risk Insurance Model (CRIM) to calculate risk-based insurance premiums and analyze how premium payments develop over time in an insurance fund.

Table 1
Climate scenarios with different levels of sea-level rise and maximum river discharges.

Name of the scenario	Rise in sea-level (cm)	Maximum Rhine discharge (m^3/s)	Maximum Meuse discharge (m^3/s)
Current	0	4150	16,000
CC24	24	4600	18,000
CC60	60	4600	18,000
CC85	85	4600	18,000
CC150	150	4600	18,000

insurance premiums of long-term contracts are incorrect if insurers assume the wrong scenario. Moreover, it provides a range of the possible levels of the risk component of flood insurance premiums if actual climate change lies within the range covered by the scenarios.

In this study, therefore, we use a scenario approach to calculate flood risk in the Netherlands. The method has been extensively described by Kok et al. (2005), Aerts et al. (2008b) and Bouwer et al. (2009). Fig. 2 shows the different steps within this approach, where both flood probabilities and potential flood damage are calculated for each dike-ring, and are then subsequently multiplied to derive flood-risk figures. Future flood risk can be calculated using climate-change scenarios to determine changes in flood probabilities together with socio-economic scenarios to derive information about how potential damage will develop over time. Finally, a Climate Risk Insurance Model (CRIM) uses the risk simulations to calculate risk-based premiums and to assess how the financial reserves of an insurance fund ('Insurance capacity' in Fig. 2) will develop over time. Next, each of the components in Fig. 2 will be discussed in detail.

2.1. Climate change scenarios and calculations of flood probabilities

Flood probability calculations for different climate-change scenarios are described in detail by Aerts et al. (2008b). Here we summarize the methodology and results. It is assumed that all levee systems in the Netherlands comply with the legal safety standards in the year 2015, because several upgrading activities are currently ongoing. Hence, the year 2015 is taken as 'the current situation' and flood probabilities for the year 2015 are as reflected in Fig. 1, and vary across the dike-ring areas from 1/10,000 to 1/1250. Table 2 shows the current flood return period per dike-ring (left column). For example, for dike-ring number 1 (the dike-ring called 'Schiermonnikoog'), the value 1/2000 means that the current flood probability is 1 in 2000 years.

For the estimation of future flood probabilities, we use the approach described by Aerts et al. (2008b), which was also used by the Dutch Deltacommissie (2008). In this method, climate change projections for the years 2040 and 2100 for the Netherlands were provided by the Royal Dutch Meteorological Institute (KNMI) (van den Hurk et al., 2006). Table 1 shows the four different climate-change scenarios as a combination of projected sea-level rise (24, 60, 85 and 150 cm) and maximum river discharges from the rivers Rhine and Meuse, which are, respectively, 16,000 or 18,000 m^3/s and 4,150 or 4,600 m^3/s (e.g. Aerts et al., 2006). The 24 cm sea-level rise scenario corresponds to a scenario of low sea-level sensitivity[3] and a 1 °C increase in global temperature in 2050, while the 60 and 85 cm sea-level rise scenarios correspond to, respectively, a low and high scenario of sea-level rise sensitivity and a 2 and 4 °C increase in global temperature in 2100 (van den Hurk et al., 2006). The 150 cm sea-level rise scenario can be considered as a worst-case scenario for the year 2100.[4]

For the hydrological simulations, the Hydra B models (e.g. de Vries, 2000) and HBV-SOBEK models for the inland river dike-ring areas (Linde et al., 2009) were used. These models used the climate-change scenarios as an input to simulate future maximum water levels (that belong to the safety standard) for each dike-ring area. The next step is to calculate the future flood probability by translating the increase in maximum water levels to a change in flood probability. For this we use the 'Decimal Height' parameter, which was used by Aerts et al. (2008b) to estimate the required elevation in dike height that lowers the flood probability by a factor of 10 (see also van

[3] Sea-level sensitivity is defined as sea-level rise per degree of global warming (see van den Hurk et al., 2006).

[4] As a comparison, the 'Second Delta Committee' used a sea-level rise scenario of 130 cm as a high-end scenario for the year 2100 for the Netherlands (Deltacommissie, 2008).

Table 2
Current and projected future flood return periods for the 53 dike-ring areas in the Netherlands. The climate-change scenarios are described in Table 1.

Number dike-ring	Name dike-ring (in Dutch)	Return period under climate scenario				
		Current	CC24	CC60	CC85	CC150
1	Schiermonnikoog	1/2000	1/662	1/126	1/40	1/2
2	Ameland	1/2000	1/662	1/126	1/40	1/2
3	Terschelling	1/2000	1/855	1/239	1/98	1/10
4	Vlieland	1/2000	1/662	1/126	1/40	1/2
5	Texel	1/4000	1/1325	1/252	1/80	1/4
6	Friesland en Groningen	1/4000	1/1325	1/252	1/80	1/4
7	Noordoostpolder	1/4000	1/4000	1/1064	1/252	1/4
8	Flevoland	1/4000	1/4000	1/1064	1/252	1/4
9	Vollenhove	1/1250	1/1250	1/333	1/79	1/1
10	Mastenbroek	1/2000	1/747	1/146	1/132	1/79
11	IJsseldelta	1/2000	1/783	1/149	1/127	1/61
12	Wieringen	1/4000	1/1325	1/252	1/80	1/4
13	Noord-Holland	1/10000	1/4273	1/1194	1/492	1/49
14	Zuid-Holland	1/10000	1/5012	1/1778	1/866	1/133
15	Lopiker- en Krimpenerwaard	1/2000	1/632	1/111	1/80	1/7
16	Alblasserwaard en Vijfheerenlanden	1/2000	1/957	1/299	1/184	1/15
17	IJsselmonde	1/4000	1/2524	1/625	1/311	1/8
18	Pernis	1/10000	1/6918	1/3196	1/1492	1/36
19	Rozenburg	1/10000	1/6918	1/3196	1/1492	1/36
20	Voorne-Putten	1/4000	1/1816	1/556	1/244	1/29
21	Hoeksche Waard	1/2000	1/928	1/158	1/58	1/2
22	Eiland van Dordrecht	1/2000	1/1002	1/201	1/88	1/3
23	Biesbosch	1/2000	1/1002	1/201	1/88	1/3
24	Land van Altena	1/2000	1/632	1/95	1/75	1/12
25	Goeree-Overflakkee	1/4000	1/1816	1/556	1/244	1/29
26	Schouwen Duivenland	1/4000	1/1709	1/478	1/197	1/20
27	Tholen en St. Philipsland	1/4000	1/1709	1/478	1/197	1/20
28	Noord Beveland	1/4000	1/1709	1/478	1/197	1/20
29	Walcheren	1/4000	1/1709	1/478	1/197	1/20
30	Zuid Beveland west	1/4000	1/1709	1/478	1/197	1/20
31	Zuid Beveland oost	1/4000	1/1709	1/478	1/197	1/20
32	Zeeuwsch Vlaanderen	1/4000	1/1709	1/478	1/197	1/20
33	Kreekrakpolder	1/4000	1/4000	1/1233	1/512	1/21
34	West-Brabant	1/2000	1/1002	1/204	1/85	1/3
34a	Geertruidenberg	1/2000	1/928	1/196	1/120	1/10
35	Donge	1/2000	1/632	1/92	1/77	1/13
36	Land van Heusden/de Maaskant	1/1250	1/466	1/82	1/78	1/63
37	Nederhemert	1/1250	1/498	1/79	1/68	1/31
38	Bommelerwaard	1/1250	1/498	1/87	1/80	1/53
39	Alem	1/1250	1/466	1/87	1/84	1/67
40	Heerewaarden	1/500	1/186	1/35	1/33	1/26
41	Land van Maas en Waal	1/1250	1/466	1/90	1/89	1/87
42	Ooij en Millingen	1/1250	1/609	1/224	1/222	1/222
43	Betuwe, Tieler- en Culemborgerwaarden	1/1250	1/609	1/224	1/219	1/187
44	Kromme Rijn	1/1250	1/789	1/387	1/362	1/252
45	Gelderse Vallei	1/1250	1/676	1/269	1/269	1/179
46	Eempolder	1/1250	1/1250	1/333	1/79	1/1
47	Arnhemse- en Velpsebroek	1/1250	1/676	1/269	1/269	1/269
48	Rijn en IJssel	1/1250	1/527	1/167	1/167	1/167
49	IJsselland	1/1250	1/636	1/230	1/230	1/229
50	Zutphen	1/1250	1/624	1/219	1/219	1/217
51	Gorssel	1/1250	1/625	1/219	1/219	1/214
52	Oost Veluwe	1/1250	1/627	1/223	1/220	1/218
53	Salland	1/1250	1/626	1/222	1/217	1/197

Dantzig, 1960). This parameter is known for each dike-ring and is not similar for all dike-ring areas because of their distinct geographical position and their different degrees of complexity of their water system. The parameter varies from around 80 cm in river dike-rings to 30 cm in inter tidal dike-ring areas (Klijn et al., 2007; Aerts et al., 2008b). This means, for example, that the flood probability of river dike-ring areas approximately increases by a factor 10 if maximum water levels rise by 80 cm. Since we can assume that current dike heights equal the maximum water level associated with their flood probability standard, we can use the 'Decimal Height' parameter to translate an increase in maximum water levels into a change in flood probability. Obviously, this method is a global approach, and a full probabilistic approach would be preferred. This would, however, go beyond the goal of this paper, which is to derive insights into future flood-risk projections and insurance premiums using a wide range of climate scenarios.

We can estimate the future flood probability by multiplying the current probability times the Decimal Height factor. The results are shown in Table 2. Overall, the results indicate that the scenario with 24 cm sea-level rise can already result in a considerable increase in the flood probability. On average, over all dike-ring areas, the flood probability increases by a factor of 2 under the CC24 scenario. Increases in the flood probability are higher under the CC60, and especially under the CC85 scenario, in which the average increase corresponds to, respectively, a factor of 10 and 19. The CC150 scenario results in an extremely large increase in the flood probability. The results of the CC150 scenario are shown in Table 2 for illustrative purposes, but will not be used for the subsequent premium calculations.

Table 3
Characteristics of the socio-economic scenarios based on the WLO study (Janssen et al., 2006; Hoeven et al., 2008).

WLO scenario	Indicator	% Change in the indicator between		Number of houses in the year		
		2015 and 2040	2040 and 2100	2015	2040	2100
Regional communities (RC)	Economic growth	1.0	1.0	n.a.	n.a.	n.a.
	Population	1.0	0.9	n.a.	n.a.	n.a.
	Houses in dike-ring	0.98	0.94	4,687,090	4,593,348	4,405,865
	Houses on high elevations	−2.00	−4.08	3,359,356	3,292,168	3,157,794
Global economy (GE)	Economic growth	2.2	2.2	n.a.	n.a.	n.a.
	Population	1.1	1.12	n.a.	n.a.	n.a.
	Houses in dike-ring	1.23	1.38	4,687,090	5,765,121	6,468,184
	Houses on high elevations	23.00	12.20	3,359,356	4,132,007	4,635,911

Note: n.a. stands for not applicable.

2.2. Flood damage calculations

The results from Aerts et al. (2008b) are used to calculate current potential flood damage and the trends in potential damage for each dike-ring area (both direct and indirect damage). This latter study used a flood damage model called the 'Damage Scanner' that is explained in Bouwer et al. (2009). This model combines three components to calculate economic losses caused by a flood for a specific situation: namely, maximum flood depth; land use (exposure); and (relative) 'stage damage functions'. The damage scanner simulates direct flood damage calculations plus a simple additional factor that represents indirect economic flood damage, such as production losses (Klijn et al., 2007).

Maximum flood depths in the current and future situations for each dike-ring are based on combining the maximum flood depths over different flood scenarios (Bouwer et al., 2009). As an input for damage exposure, we used current and future land-use information, and for each land-use class the maximum damage in € per m^2 is calculated. As an illustration, the maximum flood damage for residential areas, such as damage to structure and contents, is €910 per m^2 for high density urban areas, €400 per m^2 for low density urban areas, and €380 per m^2 for country side residential areas.[5] Another 9 classes for agriculture, pasture and nature complete the list of damage classes. What are called 'stage damage functions' relate the flooded depth of a particular land-use type to the flood damage incurred, as a percentage of its maximum value (e.g. Merz et al., 2004). Note that we deliberately choose land use as an indicator for damage exposure, since information on individual properties would provide too much detail, and hence be a considerable computational burden due to the large size of our case study area and the high number of required simulation runs.

An important element of the damage calculations is how land use will develop in the Netherlands over the periods 2015–2040 and 2040–2100. For this, the damage model used future land-use maps provided by Koomen et al. (2008), which were developed using a land use model under the assumption of different socio-economic projections. The socio-economic scenarios were adapted from the WLO study (Welvaart en Leefomgeving – The Future of the Dutch Natural and Built Environment) and are described by Janssen et al. (2006) and Hoeven et al. (2008). The WLO scenarios provide projections for trends in the Dutch economy, population, and the number of houses. These trends indicate how future flood exposure can develop, and are needed to calculate average premiums per house for each dike-ring. We used two scenarios to compute the development of future damage: namely, a high-growth scenario "Global Economy" (GE), and a low-growth scenario "Regional Communities" (RC). Table 3 shows the characteristics of these scenarios.

[5] As a comparison, the average price of a house in The Netherlands is approximately €240,000 (December 2009 values).

The geographical characteristics of some dike-ring areas make the calculation of flood damage rather complex. It appears that with sea-level rise, both the potential extent and the inundation depth of a flood will increase. Hence, when anticipating sea-level rise with dike re-enforcement, we may maintain the probability of a coastal flood at the 2015 level. Nevertheless, the consequence of a flood in 2100 will be even larger because the extent and depth of a flood will be larger. The explanation for this is that heightening the dikes also deepens the low-lying 'bathtub' behind the dike, and hence the expected maximum inundation levels.

Table 4 shows part of the results of the damage simulations: namely, for the current situation and for a combination of two different climate-change scenarios (scenario CC24 and CC85, see Table 2) with either the RC and GE socio-economic scenarios. For example, the current potential flood damage for dike-ring 1 (Schiermonnikoog) is €114 million. The potential flood damage under the high economic-growth scenario (GE) is much higher than the potential damage calculated according to the low-growth scenario (RC), especially in 2100. These results show that socio-economic developments, as reflected here in the RC and GE scenarios, can have a large influence on potential future flood damage. As an illustration, for dike-ring 1 the projected damage is €597 million and €776 million in 2100 under, respectively, the RC and GE scenarios and 85 cm of sea-level rise. Also, the effect of a climate-change scenario with greater sea-level rise is to considerably increase potential flood damage, as the large differences in results between the CC24 and CC85 scenarios show.

2.3. Climate Risk Insurance Model (CRIM)

In this subsection a Climate Risk Insurance Model (CRIM) will be specified for the determination of premiums over time and the development of an insurance fund. This model is based on the characteristics of the flood insurance program identified in Section 1. Premiums are risk-based and differentiated across the dike-ring areas, which reflects the spatial distribution of flood probabilities and expected flood damage in the Netherlands because each dike-ring area has its own closed flood protection system. Our model reports the average flood insurance premium of a dike-ring area. In practice insurers may apply a more refined–spatially distributed – premium differentiation within a dike-ring area that reflects exposure of the individual policy-holder: e.g. premiums could increase with the insured value. Kunreuther et al. (2009) highlight that risk-based premiums are a fundamental principle that should be adhered to in a natural disaster insurance scheme, since they provide a price signal of risk that can steer development towards low-risk areas and provide incentives for risk reduction. The insurance scheme is compulsory, meaning that all households in the Netherlands are covered by insurance and pay premiums. Advantages of compulsory insurance are that it creates a sufficiently large

Table 4
Potential flood damage per dike-ring area (in million €) for the current situation and under four combinations of future climate and socio-economic scenarios (see Tables 1 and 3).

Number	Name	Climate and socio-economic scenario				
dike-ring (Fig. 2)	dike-ring (in Dutch)	Current	RC2040 and CC24	GE2040 and CC24	RC2100 and CC85	GE2100 and CC85
1	Schiermonnikoog	114	209	213	597	776
2	Ameland	381	620	685	2048	2405
3	Terschelling	254	450	455	1440	1694
4	Vlieland	25	51	125	258	448
5	Texel	2918	5156	4857	13995	20499
6	Friesland en Groningen	761	1735	2073	8295	12699
7	Noordoostpolder	2665	5833	6420	13921	30682
8	Flevoland	8882	16,948	22,877	66,041	102,785
9	Vollenhove	3362	7767	10,964	46,093	92,134
10	Mastenbroek	1903	3592	4095	11,127	15,525
11	IJsseldelta	1523	2251	3626	10,041	14,775
12	Wieringen	3933	8897	16,969	22,181	85,369
13	Noord-Holland	4568	8289	12,031	26,270	45,789
14	Zuid-Holland	23,600	43,824	64,690	210,595	302,988
15	Lopiker- en Krimpenerwaard	6471	12,097	13,712	42,723	46,440
16	Alblasserwaard en Vijfheerenlanden	27,026	51,443	58,439	148,359	208,298
17	IJsselmonde	12,815	18,730	27,162	55,297	88,765
18	Pernis	634	1209	1361	3734	4830
19	Rozenburg	1776	3291	3098	10,900	11,014
20	Voorne-Putten	11,420	20,160	28,091	59,468	105,978
21	Hoeksche Waard	4060	10,517	11,213	35,152	52,433
22	Eiland van Dordrecht	11,420	17261	31,699	62,260	104,902
23	Biesbosch	76	n/a	n/a	n/a	n/a
24	Land van Altena	3045	6410	6796	16,048	53,449
25	Goeree-Overflakkee	2665	8855	18,448	32,435	82,441
26	Schouwen Duivenland	3172	6847	7340	21,709	32,068
27	Tholen en St. Philipsland	1649	3044	3352	9601	13,382
28	Noord Beveland	508	1072	1168	3698	4661
29	Walcheren	10,151	13,292	19,362	48,932	72,644
30	Zuid Beveland west	6725	12,842	22,147	52,553	94,746
31	Zuid Beveland oost	3045	6119	11,981	19,892	70,808
32	Zeeuwsch Vlaanderen	1142	1931	2310	6133	9594
33	Kreekrakpolder	19	50	56	178	235
34	West-Brabant	7105	35,526	41,018	414,080	864,635
35	Donge	4441	8530	10,446	26,978	67,637
36	Land van Heusden/de Maaskant	4822	7226	10,454	21,378	58,918
37	Nederhemert	4	8	8	19	29
38	Bommelerwaard	3553	6278	8612	12,891	28,382
39	Alem	38	122	60	136	154
40	Heerewaarden	51	117	81	172	225
41	Land van Maas en Waal	6598	10,424	16704	29,559	52,503
42	Ooij en Millingen	1269	2277	2258	4278	7110
43	Betuwe, Tieler- en Culemborgerwaarden	17,510	29,919	46,911	71,443	154,292
44	Kromme Rijn	6979	12,363	20,730	47,805	80,288
45	Gelderse Vallei	6852	10,070	13,528	25,662	37,121
46	Eempolder	127	282	511	2305	3737
47	Arnhemse- en Velpsebroek	888	926	1550	3311	4027
48	Rijn en IJssel	6217	9543	15,255	25,735	50,030
49	IJsselland	508	952	873	1848	2505
50	Zutphen	2284	3308	3693	8646	9996
51	Gorssel	381	687	1150	2498	3032
52	Oost Veluwe	2665	4720	5901	10,624	19,182
53	Salland	6852	11,129	12,212	34,127	46,752

pool of insurance contracts and prevents potential problems with adverse selection.[6] Households pay part of flood damage via deductibles that are defined as a percentage of the flood damage that they can potentially suffer (see Zeckhauser, 1995). In the layered insurance program, insurers pay damage up to a pre-specified maximum amount (called the cap); and the government compensates remaining damage.

Citizens outside the dike-ring areas also contribute to the insurance fund via a flat rate premium based on the principle of solidarity. In general, the Dutch social welfare system is characterized by a high degree of solidarity among its residents. The co-payment of households outside the flood zones in the Netherlands may, furthermore, be rationalized on grounds that a flood causes a severe disruption of economic activities (indirect damage), which is disadvantageous for all citizens (Bočkarjova, 2007). The inhabitants of areas safe from flooding will benefit from a fast rebuilding of the capital stock and recovery of economic activities in areas where a flood event has occurred, which may justify their financial contribution to an insurance arrangement that compensates flood damage.

2.4. Insurance premiums

The Climate Risk Insurance Model (CRIM) model estimates the development over time of spatially distributed insurance pre-

[6] Adverse selection occurs when many households who live in high-risk areas purchase flood insurance, and insurers have difficulties with distinguishing low- from high-risk individuals (asymmetric information), and hence have problems charging the latter group an appropriate higher premium.

miums (i.e. which differ for each of the 53 spatial units, the number of dike-ring areas). Premiums per household are estimated as follows for each dike-ring area in the Netherlands, i (with a total $I = 53$ areas), in year t:

$$\text{premium}_{it} = \frac{l \times h \times \text{total expected damage}_{it}}{\text{total houses}_{it}} \times \text{flood probability}_{it} \quad (1)$$

In this equation, l is the premium loading factor that equals 1 for actuarially fair premiums, i.e. premiums that cover the expected value of damage per policy; and $l > 1$ represents a surcharge to cover administrative or transaction costs and an economic return (profit) for insurance companies. The term *total expected damage* is the estimated total direct damage caused by a flood in dike-ring area i at time t; h ($1 \geq h \geq 0$) is the proportion of total direct damage that represents damage to houses and furniture (Table 4); *total houses* is the total number of houses in dike-ring area i at time t; and *flood probability* is the expected flood return period (Table 2). The time subscript t indicates that the expected flood damage, the flood probability and the number of houses vary over time according to climate-change projections and expected socio-economic developments.

2.5. Development of an insurance fund

The development of the funds of the insurance sector is determined by the accumulation of collected insurance premiums over time and depletion because of payouts (insurance claims) after a flood event has occurred. The accumulation of premiums comes from the risk-based premium contributions of households living in dike-ring areas and the contributions of households living in areas of higher elevation. The latter group of households pays a flat-rate premium. The total amount of funds of the insurance sector at a specific point in time is presented by:

$$\text{insurers funds}_t = \sum_{i=1}^{I}\sum_{t=1}^{t}(\text{premium}_{it} \times \text{total houses}_{it}) + \sum_{t=1}^{t}\text{flat premium}_t - \sum_{i=1}^{I}\sum_{t=1}^{t} c \times \text{damage}_{it} \quad (2)$$

where premium_{it} is the risk-based premium charged in the dike-ring areas that is defined by equation 1; flat premium is the total contribution to the fund by households living outside the flood zones; and c is the proportion of flood damage (damage_{it}) that is covered by insurance ($1 \geq c \geq 0$). In other words, the sum of $c \times \text{damage}_{it}$ indicates the total payouts of the insurance sector at time t to reimburse property damage caused by a flood in dike-ring area i. In all our calculations of insurers' funds, they are assumed to grow over time according to an expected return on investments of those funds of 4% per year.

2.6. Insurance funds of a three-layered insurance program

Households and the government carry part of the flood risk in addition to the insurance sector in the layered insurance program (see the discussion in Section 1). For reasons of simplicity, reinsurance is not explicitly considered, and the insurance fund can be considered as a fund for the insurance sector as a whole. It is assumed that households pay for a certain percentage of flood damage via a deductible, $(1 - c)$, which is defined as a proportion of flood damage to their property (damage_{it}). Formally, the total amount of flood damage paid for by households at time t is:

$$\text{household layer}_t = \sum_{i}^{I}(1 - c) \times \text{damage}_{it} \quad (3)$$

The insurance sector pays the remaining damage subject to a pre-specified maximum amount CAP. The total amount of flood damage paid by the insurance sector is then defined by:

$$\text{payout claims}_t = \begin{cases} \text{CAP} & \text{for } \sum_{i=1}^{I}\text{damage}_{it} - \text{household layer}_t > \text{CAP} \\ \sum_{i=1}^{I}\text{damage}_{it} - \text{household layer}_t & \text{for } \sum_{i=1}^{I}\textit{damage}_{it} - \text{household layer}_t < \text{CAP} \end{cases} \quad (4)$$

The government compensates the damage that remains after the payouts of the insurance sector and the amounts households pay via deductibles. This government compensation takes the form of reinsurance for which insurance companies pay the actuarially fair price to the government. Thus the amount of flood damage compensated by the government equals:

$$\text{government layer}_t = \sum_{i=1}^{I}\text{damage}_{it} - \text{household layer}_t - \text{payout claims}_t \quad (5)$$

The development of the insurance fund over time can now be represented as:

$$\text{insurers funds}_t = \sum_{i=1}^{I}\sum_{t=1}^{t}(\text{premium}_{it} \times \text{total houses}_{it}) + \sum_{t=1}^{t}\text{flat premium}_t - \sum_{t=1}^{t}\text{payout claims}_t \quad (6)$$

3. The projected development of risk-based insurance premiums over time

The future projections of flood probabilities and damage potential (e.g. Tables 2 and 4) are used to calculate flood risk for each dike-ring. Based on these values, Eq. (1) is used to derive risk-based premiums over time for different climate and socio-economic scenarios (RC and GE). These risk-based premiums are actuarially fair, which means that they are equal to the expected value of the loss; i.e. probability times damage. In other words, it is assumed that insurers do not charge a profit margin, and in Eq. (1) the loading factor $l = 1$.[7] The resulting flood insurance premium values for all scenarios are presented in Table 5. Table 5 shows the premiums under each scenario of either climate change or socio-economic change for the years 2015, 2040, and 2100. For example,

[7] As a simplification, bureaucratic cost or cost of holding capital are not considered here. It would be very difficult to assess their development over time and, thereby, including such costs would add to the uncertainty of our estimates, while these cost categories are less relevant for the objective of our study; i.e. to show the effects of climate change and economic growth on the risk component of flood insurance premiums over time.

Table 5
Flood insurance premium development in € per year for the current situation, two climate-change scenarios (CC24 and CC85, Table 1) and two socio-economic scenarios (RC and GE, Table 3) for the years 2040 and 2100.

Number dike-ring (Fig. 2)	Name of dike-ring (in Dutch)	Socio-economic or climate scenario						
		Current (€/year)	RC 2040 (€/year)	RC 2100 (€/year)	GE 2040 (€/year)	GE 2100 (€/year)	CC24 (€/year)	CC85 (€/year)
1	Schiermonnikoog	87	162	482	132	427	267	4622
2	Ameland	106	176	608	155	486	327	5659
3	Terschelling	119	215	717	173	575	284	2567
4	Vlieland	44	90	480	178	569	137	2371
5	Texel	103	185	524	139	522	316	5473
6	Friesland en Groningen	0	1	4	1	4	1	16
7	Noordoostpolder	22	50	125	44	187	23	116
8	Flevoland	17	33	133	35	141	17	87
9	Vollenhove	60	142	877	159	1194	61	255
10	Mastenbroek	64	124	399	112	379	141	647
11	IJsseldelta	31	46	215	59	216	64	324
12	Wieringen	89	206	535	313	1402	275	4753
13	Noord-Holland	1	2	5	2	6	2	18
14	Zuid-Holland	1	2	10	2	10	2	13
15	Lopiker- en Krimpenerwaard	31	58	215	53	159	45	142
16	Alblasserwaard en Vijfheerenlanden	123	239	719	216	687	199	1008
17	IJsselmonde	15	22	67	25	73	24	199
18	Pernis	23	45	145	40	128	34	165
19	Rozenburg	23	44	153	33	105	34	167
20	Voorne-Putten	34	61	189	68	229	77	594
21	Hoeksche Waard	47	125	436	106	443	81	1610
22	Eiland van Dordrecht	91	140	526	205	603	164	4753
23	Biesbosch	248	1	1	1	1	401	5970
24	Land van Altena	62	134	350	113	794	202	1765
25	Goeree-Overflakkee	28	94	358	156	620	64	523
26	Schouwen Duivenland	41	89	295	76	297	98	919
27	Tholen en St. Philipsland	34	64	211	56	201	82	738
28	Noord Beveland	28	61	220	53	189	68	613
29	Walcheren	39	52	199	60	201	93	838
30	Zuid Beveland west	43	83	355	114	436	102	922
31	Zuid Beveland oost	81	165	560	258	1358	192	1741
32	Zeeuwsch Vlaanderen	4	8	25	7	27	11	95
33	Kreekrakpolder	137	371	1365	326	1226	140	1141
34	West-Brabant	17	86	1046	79	1488	34	424
34.a	Geertruidenberg	33	1	1	1	1	61	495
35	Donge	44	87	287	85	490	143	1232
36	Land van Heusden/de Maaskant	17	27	82	31	155	75	397
37	Nederhemert	190	386	990	320	1068	614	2325
38	Bommelerwaard	127	229	490	250	735	410	1552
39	Alem	135	442	512	174	395	582	3068
40	Heerewaarden	166	390	601	215	535	715	3326
41	Land van Maas en Waal	36	58	172	74	209	208	1224
42	Ooij en Millingen	136	248	487	196	551	284	812
43	Betuwe, Tieler- en Culemborgerwaarden	87	152	378	190	557	183	529
44	Kromme Rijn	14	26	104	35	119	15	17
45	Gelderse Vallei	40	60	159	64	156	41	42
46	Eempolder	24	54	456	77	503	24	25
47	Arnhemse- en Velpsebroek	14	15	57	20	47	18	26
48	Rijn en IJssel	62	98	274	124	363	151	497
49	IJsselland	39	74	151	54	139	57	102
50	Zutphen	75	111	301	98	237	111	205
51	Gorssel	50	93	352	124	291	75	139
52	Oost Veluwe	38	69	161	68	198	56	105
53	Salland	48	79	252	69	236	71	134

the premium calculated using the socio-economic scenario RC assumes that the flood probability remains at the level of 2015. And, likewise, the premium calculated for the climate-change scenario CC85 assumes 85 cm sea-level rise in 2100 and higher maximum river discharges, while the damage potential remains at the level of 2015. The reason for these separate calculations is to examine the relative influence of the different trends on the development of premiums. All values are in 2010 Euros.

3.1. Geographical distribution of risk-based premiums under climate and socio-economic change

Flood insurance premiums in the current situation vary from about €1 per year in dike-ring 14 to €250 per year in dike-ring 23, with an average premium per household across all dike-rings of about €34 per year. At first sight premiums may appear to be too low to provide a strong signal for mitigation, but it should be noted that these premium levels are averages for all households in a dike-ring area and that risk-based premiums of individual households may be considerably higher due to an unequal distribution of flood risk within a dike-ring area. The high premium in dike-ring 23 can be explained by the fact that it is an inter-tidal area under the influence of both sea-level rise and river discharges. It is, moreover, the dike-ring area with the lowest population density of all areas, which implies that a relatively low number of households have to pay premiums for a relatively high risk area. Dike-ring 14, on the other hand, is the largest dike-ring of the Netherlands with the highest safety standard of 1/10,000 (see Fig. 1). About 3,500,000

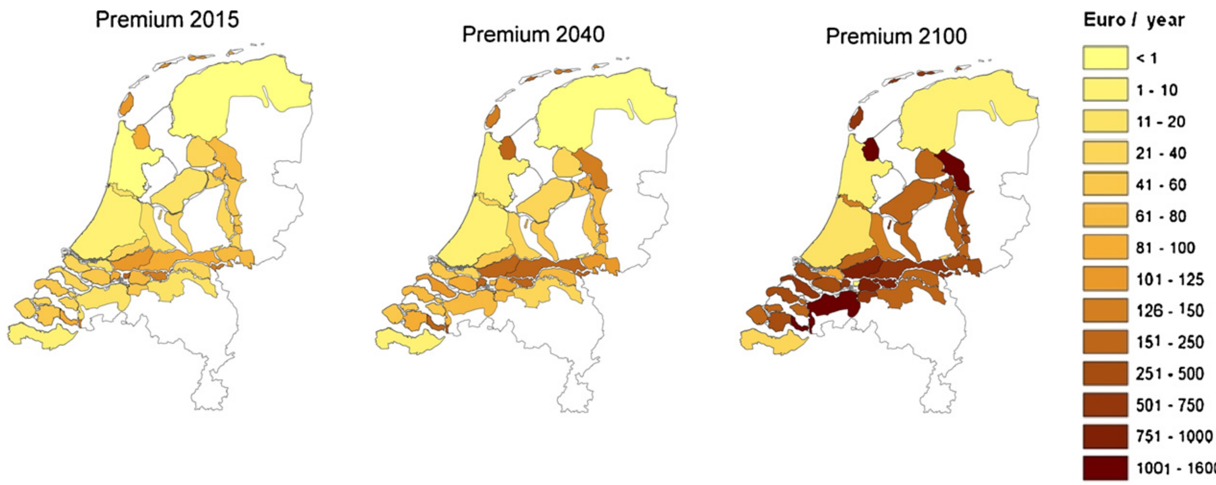

Fig. 3. Spatial distribution of premiums in € per year for the years 2015, 2040 and 2100 assuming the RC socio-economic scenario (see Table 3) and the climate-change scenarios CC24 and CC85 for, respectively, the years 2040 and 2100 (Table 1).

people live and work in this area in locations up to 7 m below sea level. Table 4 shows that the maximum damage of €23 billion in 2015 in dike-ring 14 is not that high considering its large exposure to flooding. The complete area of the dike-ring will not be flooded at the same time, so that only a smaller part of the 3,500,000 people are vulnerable to storm surges from sea and river floods. Hence, the potential flood damage will be spread over many households if premiums are set per dike-ring area, and as a result premiums are relatively low.

Overall, the high economic-growth scenario (GE) results in a slightly larger increase in flood insurance premiums than the low economic-growth scenario (RC). In particular, on average over the dike-ring areas premiums increase by 93% in 2040 and by 641% in 2100 under the RC scenario compared with 2015, while the premium increase under the GE scenario is 102% and 797% in, respectively, the years 2040 and 2100. If climate change were to result in a 24 cm sea-level rise in 2040 and 85 cm in 2100, then the effect of climate change on flood insurance premiums would outweigh the effect of socio-economic developments. This is the case because on average over the dike-ring areas, premiums under the CC24 scenario increase by 125% and premiums increase by 1784% under the CC85 scenario compared with 2015. Table 5 shows that premiums under the climate-change scenario are the highest and reach a value of over €5000 (in 2100) for some dike-ring areas. However, there are large regional differences in the effects of socio-economic and climate change on flood insurance premiums, as will be explored below.

The geographical distribution of flood insurance premiums over all dike-ring areas in the years 2015, 2040 and 2100 is presented in Fig. 3. The premiums are computed for the RC socio-economic scenario and assuming, 24 cm sea-level rise in the year 2040 and 85 cm in 2100. In general, the dike-ring areas with the lowest concentrations of population in combination with a relatively low protection level have the highest flood risk per household, and therefore, the highest premiums. These are, in general, the river dike-ring areas with a current flood probability of 1/1250 and the inter-tidal dike-ring areas with a current flood probability of 1/2000. In addition, flood probability, and hence flood risk and insurance premiums, show the largest projected increase over time in those areas where both sea-level rise and river discharges have an influence on the flood probability. These are again the dark-shaded intertidal dike-ring areas in Fig. 3. In contrast, the flood insurance premiums in the dike-ring areas near the coast with a high concentration of population and economic values remain rather constant over time. In summary, the future projections of flood insurance premiums suggest that premiums may increase considerably due to socio-economic and climate change, but that the increase is very region specific even in a small country like the Netherlands.

Fig. 4 shows the results of premium calculations for three dike-ring areas that differ in both geographic conditions and their concentration of economic values. The development of premiums is shown between 2015 and 2100, and calculated by assuming a linear trend between 2015–2040 and 2040–2100. We note that this is a simplistic representation because the trend may be nonlinear. Nevertheless, the assumption may not be very restrictive for the comparative analyses aimed at here. Dike-ring 14 has been introduced above and is the largest dike-ring in the Netherlands. Dike-ring 36 is an area near the river Meuse and only the discharge peaks of the river determine the flood probability, which is currently 1/1250. This area is not under the influence of sea-level rise. Dike-ring 29 is situated near the coast and has relatively low economic activity and a low population density. It is, however, historically an important area in the Netherlands since one of the most devastating storm surges in Dutch history hit this area in 1953. The flood probability of this coastal area is currently 1/2000.

A first examination of Fig. 4 indicates the relatively low value of the premiums for dike-ring 14, as opposed to the relatively high premiums for dike-ring 29. This can be attributed to the relatively high protection level in dike-ring 14, and hence flood risk defined as probability times damage is low, even though the projected flood damage of dike-ring 14 is higher than of dike-ring 29 (see Table 4). Moreover, in dike-ring 14 about 1,600,000 households pay a premium and, as stated above, only a small number of these households will suffer damage during a flood. On the other hand, in dike-ring 29 only 49,000 households are able to contribute to flood insurance, and almost all of these houses will be inundated in the event of a dike failure. The figure for dike-ring 36 shows more or less intermediate premium values compared with the other two figures.

Another interesting feature of Fig. 4 is the relative rapidly increase in premium levels after the year 2040 under the climate change scenario. This is because the climate change scenario shows an acceleration especially in sea-level rise and peak river discharges after the middle of this century. For dike-rings 14, 29 and 36, the flood probability increases by a factor of 2–3 between 2015 and 2040. For the period 2040–2100, flood probabilities for these areas increase by a factor of 16–20. This observation is very much in line with the IPCC, 2007 report, which states that large ice

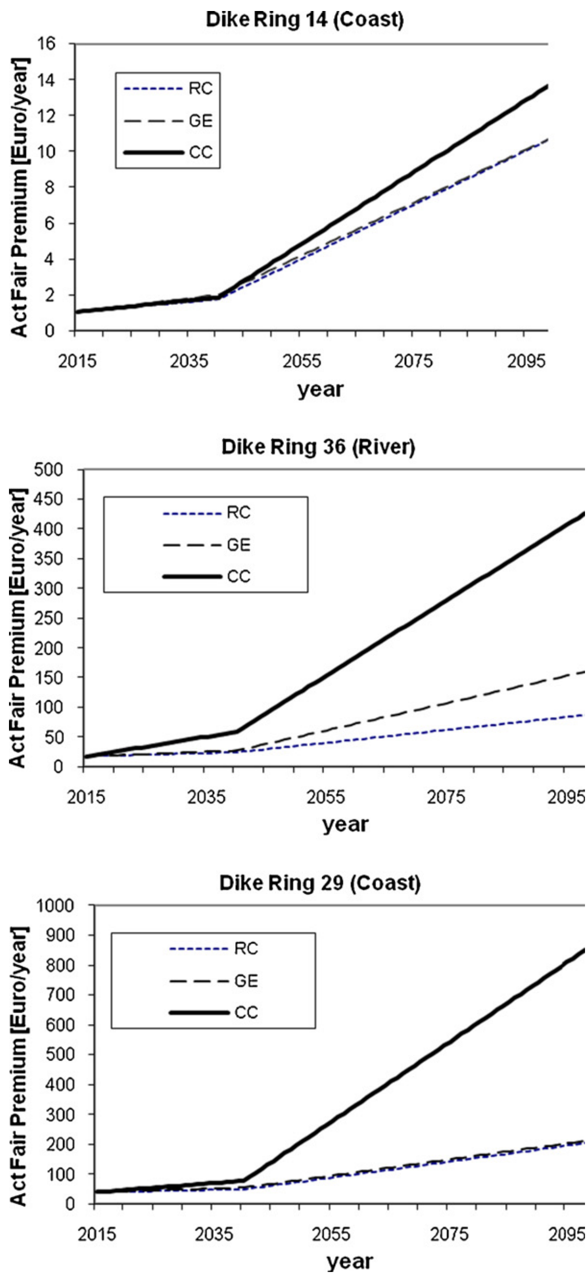

Fig. 4. Flood insurance premium development over time, according to the regional communities (RC), global economy (GE) and climate change (CC) scenarios. Note that premium developments for dike-ring 14 and 29 are similar for both the RC and GE scenarios.

sheets are expected to show accelerated ice melt in the second half of this century. The most rapid increase in premiums can be observed in the coastal dike-ring areas (14 and 29), which indicates that accelerated sea-level rise has a larger effect on flood risk compared with increasing river discharges.

Fig. 4, furthermore, shows the relative influence of land-use change on flood insurance premiums as compared with the influence of climate change. Up to the year 2040, both trends have more or less a similar increasing-effect on premiums. However, in the period 2040–2100, the effects of climate change on premium development is much higher than the effect of land-use change under the high growth scenario (GE). This is in line with the findings of Aerts et al. (2008b) who conclude that the increase in flood risk in the Netherlands shows similar rates for both the GE scenario in 2100 and a maximum sea-level rise of 60 cm in 2100. The difference between the effect of the GE and RC scenarios is negligible for the coastal dike-ring areas 14 and 29. In contrast, for dike-ring 36 the influence of the GE scenario on the development of the flood insurance premium is much higher compared with that of the RC scenario. This implies that urban development is much higher in the GE scenario compared with the RC scenario, at least for this dike-ring area.

3.2. Risk-based premiums over time of long-term insurance contracts with durations of 5, 10 and 15 years

Insurers can price long-term flood insurance contracts by assuming a certain likely scenario of climate change and socio-economic change that influences flood risk over the duration of the contract. In order to get an idea of the influence of such scenarios on estimated flood insurance premiums of long-term contracts, we examined the effect of several representative scenarios on fixed insurance premiums for long-term insurance contracts with various durations. Analogous with commonly employed mortgage periods (Kunreuther and Michel-Kerjan, 2009), premiums are computed for three contract types with durations of 5, 10 and 15 years. The premium development for each contract type has subsequently been examined over time periods up to 2040 by assuming the climate-change scenarios CC24 and CC60 and either low or high economic growth (RC and GE). The premiums for the contracts with several durations over different time periods under these scenarios are shown in Table 6. The premiums shown are averaged across all dike-ring areas. The results provide an indication of how far insurance premiums would deviate from the true development of risk if insurers assume the wrong climate change scenario (e.g. CC24 instead of CC60), or the wrong socio-economic scenario (e.g. RC instead of GE) in their premium calculations made at the beginning of the long-term insurance contract.

Table 6 shows the results. Overall, climate change has a greater influence on the premium increase than socio-economic changes. This highlights the need for insurance companies to have adequate predictions of climate change in setting long-term flood insurance premiums. Furthermore, the effect of the contract duration also shows a clear pattern. Long-term 15-year contracts obviously start with relatively high premiums compared with 5-year contracts (~ 30- 100% higher). In the real world the actual climate change that will materialize is unknown at the time when premiums are determined, which can result in considerable problems with pricing the long-term flood insurance according to the results in Table 6. For example, suppose that in the year 2015 the insurer suspects that climate change will develop according to the CC24 scenario until 2040, but that the true scenario is CC60, while the insurer correctly predicts that the socio-economic scenario is RC. In that case, premiums would be moderately underpriced for the 5-year contract (€16 per year), while premiums would be considerably too low for the 10-year (€30 per year) and 15-year (€36 per year) contracts. Evidently, premiums would be even more underpriced if the correct socio-economic scenario is GE instead of RC. The results show that mispricing can be a serious issue even for contracts with a duration of 5 or 10 years. Clearly, in the face of this uncertainty the insurance company is better off to keep contracts as short as possible, because premium shortfall compared with expected payouts of claims is lowest with 5-year contracts. In a competitive insurance market like in the Netherlands, the likely outcome will be that insurers will restrict their policies to short periods. For consumers the contrary holds and they would prefer the contract with the longest duration when insurers underestimate the effects of climate change. At a certain point, the insurer will realize that its

Table 6
Development of flood insurance premiums for long-term contracts with durations of 5, 10 and 15 years between 2015 and 2040. Premiums are given as fixed yearly amounts and are averaged over the dike-ring areas and estimated under the CC24 or CC60 climate-change scenarios (Table 1) and either low or high economic growth (RC2040 and GE2040).

Contract duration	Scenarios CC24 and RC2040			Scenarios CC60 and RC2040		
	5 years (€/year)	10 years (€/year)	15 years (€/year)	5 years (€/year)	10 years (€/year)	15 years (€/year)
Period 2015–2020	25	30	33	41	60	79
Period 2020–2025	33	30	33	79	60	79
Period 2025–2030	39	41	33	118	138	79
Period 2030–2035	44	41	50	157	138	196
Period 2035–2040	50	53	50	196	215	196
Period 2040–2045	56	53	50	235	215	196
	Scenarios CC24 and GE2040			Scenarios CC60 and GE2040		
	5 years (€/year)	10 years (€/year)	15 years (€/year)	5 years (€/year)	10 years (€/year)	15 years (€/year)
Period 2015–2020	34	42	42	46	69	69
Period 2020–2025	50	42	42	91	69	69
Period 2025–2030	65	73	42	137	159	69
Period 2030–2035	81	73	96	187	159	227
Period 2035–2040	96	104	96	227	250	227
Period 2040–2045	112	104	96	272	250	227

premiums are too low and correspondingly revise its climate-change scenario and premiums upward.

Suppose that the insurer acts prudently and sets the premiums according to the high climate-change scenario in 2015, while it adjusts its premiums downward if the low climate-change scenario materializes. In that case, there would be an interest for the consumer to choose the short-term 5-year contract. The longer-term contracts are less attractive for the consumer, because, if climate change turns out to follow the CC24 scenario instead of CC60 then the insurer would charge lower premiums for its new contracts, while the consumer would be stuck with a high premium for a long-term contract. Along the same lines, it is evident that consumers would lose money if they choose a long-term contract and the insurer incorrectly expects that CC60 is the right climate-change scenario, while in fact CC24 is correct and at a certain point in time lower premiums will be charged that more correctly reflect risk. The development of the premiums over the different time periods indicates that considerable adjustments are needed to reflect the change in risk, especially if the high economic-growth scenario (GE) or high climate-change scenario (CC60) are used in setting premiums.

The development of capital reserves over time is subsequently examined for long-term flood insurance contracts with durations of fixed premiums of 5 and 15 years. Claim payouts due to flood events are not considered here since the main objective of the estimations is to examine the consequences of (incorrect) expectations about climate change on the relative accumulation of insurance funds resulting from premiums that are set according to different climate-change scenarios. The accumulation of capital reserves for these long-term insurance contracts has been examined under the two climate-change scenarios CC24 and CC60 and the GE scenario of high socio-economic growth. Obviously, the insurer does not know beforehand (e.g. in 2015) what scenario of climate change will actually materialize. Expecting a wrong scenario implies that the development of reserves will not be in line with the actual development of risk for some time period. At one point, the insurer may realize this and revise its expectations of climate change. However, a large shortage of funds may have already been developed in that case.

Fig. 5 shows the results. Since the flood risks from the high sea-level rise scenario (CC60) are considerably higher than those under the low sea-level rise scenario (CC24), the income from premiums over time assuming the 60 cm sea-level rise will also be higher. In the year 2045, about €16 billion will be generated through the collection of premiums assuming a 60 cm sea-level rise, while this is €7 billion if premiums are set in accordance with the 24 cm sea-level rise scenario. These results indicate that the differences in fund accumulation will be very different if the insurer assumes the wrong scenario of climate change in determining premiums, especially after the period 2025–2030. For example, if the insurer incorrectly expects in 2015 that climate change will develop according to the CC24 scenario, while the true scenario is CC60, then it is apparent from the graph that the true development of risk is much higher than the assumed development, and therefore the shortfall in required insurance funds will be quite substantial. The shortfall in reserves in that case would be almost 50% in 2030.

The previous discussion revealed fundamental problems with the pricing of long-term flood insurance contracts in the face of uncertainty about climate and socio-economic change. Our numerical exercise using four scenarios of future risks showed that there is an incentive for either the insurance company or for the consumer to, respectively, market or purchase the short-term contract of 5 years if uncertainty exists about the true trend of climate and socio-economic change. In practice, pricing long-term

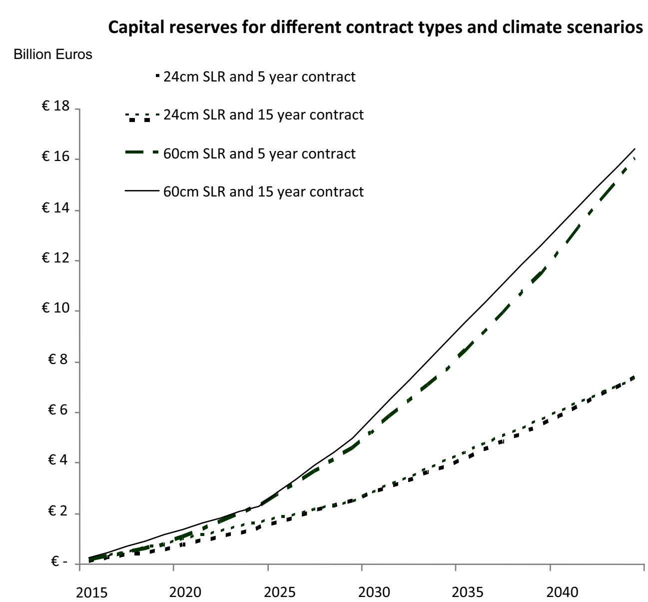

Fig. 5. Accumulation of capital reserves over time under two climate-change scenarios (CC24 and CC60) and high economic growth for two long-term insurance contracts with fixed premiums over periods of either 5 or 15 years.

risk may be even more complicated, as our models suggest, due to uncertainties in the hydrological and flood damage models, which are not quantified here and for which a mark-up on insurance premiums may be appropriate. This mark-up may increase with the contract duration should such uncertainties become larger if forecast of risks are made over longer time periods, which would decrease the attractiveness of long-term contracts even further. Moreover, the actual development of future flood risk depends on the investments of the Dutch government in the prevention of floods. These investments depend on political decision making which is inherently difficult to predict and are, therefore, not accounted for in our analysis. In practice this would be another complicating factor in the pricing of long-term contracts in addition to the uncertainty of climate change. Another challenge for insurers, which was identified in Section 3.1, is that changes in premiums can vary considerably between the different dike-ring areas.

It seems advisable to allow for variable insurance premiums in long-term contracts where premiums are adjusted within a certain range according to climate-change developments, such as sea-level rise and the increase in precipitation or maximum peak discharges of rivers. Kunreuther and Michel-Kerjan (2009) propose to overcome the problem of changes in risk by allowing for a renegotiation of contracts over time based on new information on changed weather conditions that is validated by the scientific community. For this purpose, a special risk index could be established by an independent third party. In addition to incorporating climate change, our results indicate the importance of accounting for the influence on flood-risk of socio-economic developments, such as those concerning the housing stock or population and economic growth. Establishing such a risk index over time is not a straightforward task, because it would be difficult to disentangle short-term variation in weather from long-term climate change trends. For instance, there has been considerable debate about whether the catastrophic 2005 hurricane season in the USA reflected a temporary increase in hurricane activity or whether risk will be permanently higher due to climate change and in particular higher ocean temperatures (e.g. Botzen et al., 2010). Premium increases due to (anticipated) climate change may be resisted by insurance regulators, as occurred in Florida, and may also be an issue in the Netherlands. Furthermore, the impacts of climate change on flood risk can be limited by adequate adaptation policy. The climate-change scenario presented here assumes that no adaptation measures are undertaken, which is useful to indicate the upper bound of the potential effects of climate change on premiums. However, accounting for the combined effects of climate change, socio-economic changes and adaptation policy in a risk index that can be confidently used to adjust long-term flood insurance premiums over time will be a challenge. Moreover, allowing for price changes in long-term contract makes them cease long term.

4. Long-term development of insurance funds under various flood scenarios

4.1. Private insurance fund without government intervention

The previous section presented flood insurance premiums over time according to different climate and socio-economic scenarios. These estimated premiums can now be an input to assess how an insurance fund may accumulate over time in the face of various flood scenarios. For this purpose, Eq. (2) that assumes a purely private insurance market over a period of 85 years (2015–2100) is applied. In this period, premiums accumulate in a reserve fund, which can be capitalized for the purpose of compensation of damage to policyholders caused by an extreme flood event. Our model is simplistic in the sense that we assume premium capital will grow at an interest rate of 4% and we do not address the issue of how much reinsurance capacity is needed for such a private insurance scheme. Here we analyze how much premium income is collected over time, and how this compares to potential damage triggered by low-probability high-impact flood events. In this calculation, we do not add a loading factor to the actuarially fair premiums.[8] Given the complications with pricing long-term contracts that were identified in Section 3, the premiums collected for the insurance fund are assumed to be from yearly contracts and are adjusted every year to reflect changed risk.

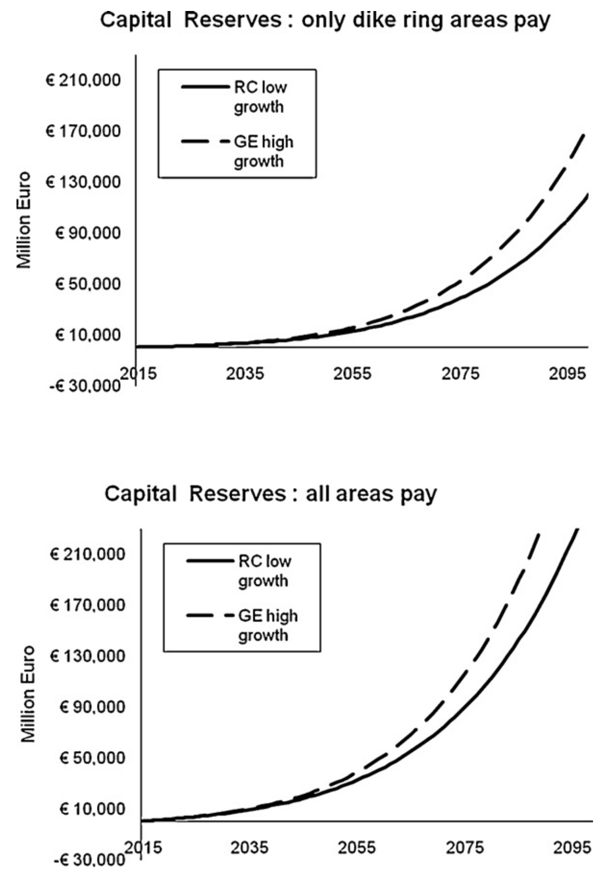

Fig. 6. Accumulation of capital reserves over time according to the low growth (RC) and high growth (GE) scenarios. The top panel shows an insurance scheme where only households from the lower lying dike-ring areas pay premiums. The panel on the bottom shows a scheme where also households from higher parts of the country pay premiums.

Fig. 6 shows how capital reserves of the insurance fund build up over time, assuming that no flood event occurs. On the left, Fig. 6 shows that the maximum reserve in the year 2100 would be €184 billion in the case of the GE scenario (high economic growth). Here, it is assumed that only the inhabitants of the dike-ring areas pay premiums. In the same Fig. 6, on the right, it is assumed that the inhabitants of the higher parts of the Netherlands would also pay a premium starting at €50 per year and gradually increasing by only 1% per year over the period 2015–2100. The maximum reserve in the year 2100 would then be around €380 billion, almost twice as much as it would be if no households located on the higher grounds were included in the insurance scheme.

Next, the influence of several series of flood damage events on the insurance fund is simulated. This imposes a requirement on insurers to compensate policyholders and decreases insurers'

[8] Administrative costs and a profit margin for shareholders would not accumulate in a reserve fund and are, therefore, not considered here.

Table 7
Flood scenarios, their presumed damage and timing.

Year	Flood scenario 1 (damage in billion €)	Flood scenario 2 (damage in billion €)	Flood scenario 3 (damage in billion €)
2020	0	4	0
2035	6	4	0
2040	0	4	0
2060	15	4	50
2075	0	4	0

financial reserves. We have constructed three different flooding scenarios with different amounts of damage and varying sequences in which the events occur (see Table 7). The first scenario describes two large floods with €6 and €15 billion in, respectively, the years 2035 and 2060. This scenario is representative for the damage that would occur because of a large river flood. The second scenario describes a series of five smaller floods that cause €4 billion damage each. The third scenario simulates an extreme storm surge from the sea, with great damage (€50 billion) that can be compared with the damage caused by Hurricane Katrina in New Orleans in 2005, or the destructive storm surge that hit the South West of the Netherlands in 1953.

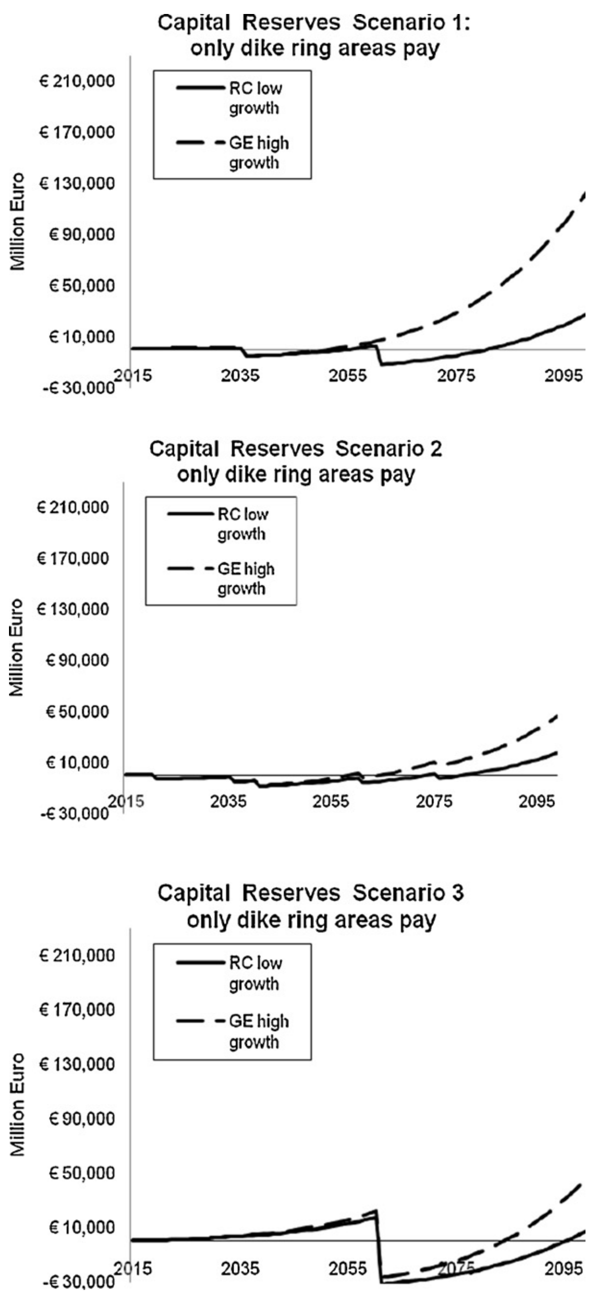

Fig. 7. Capital reserve development in a private insurance market in the Netherlands under three flood scenarios (Table 7). Scenario 1 consists of two large floods, Scenario 2 of five smaller floods, and Scenario 3 of one extreme storm surge.

Fig. 7 shows the development of the fund over time under the three flooding scenarios. From this figure it is apparent that a private market scheme may be able to handle Scenarios 1 and 2 in case of the high growth (GE) scenario, because the funds do not decrease much below zero after the flood events. Under the low growth scenario (RC), the scenarios 1 and 2 initially result in a negative balance of the capital reserve, but the reserve becomes positive again between 2065 and 2070. In this period, premiums rise more rapidly because of accelerated sea-level rise. The results of the extreme Scenario 3 show that this insurance scheme would not be able to absorb the damage inflicted by this event. We have, however, searched for an optimized premium for households located in the higher parts of the country in order to accommodate for a payout of €50 billion in the year 2060. In order to accumulate sufficient reserves to cover flood scenario 3, the premium for households in high parts needs to be initially set at €50 per year in 2015, with a subsequent increase of 1% per year. This analysis shows that a very large fund would be needed to cover flood damage through private insurance, which cannot be relied upon and will be costly.

4.2. A public-private partnership in the form of a three-layered insurance market

In this section, the development of insurance funds is examined under the same flood scenarios as in Section 4.1, but now for a three-layered insurance arrangement where the government covers damage above a pre-specified amount (cap), and households pay for part of the flood damage through deductibles. This is done by applying Eqs. (3)–(6) described in Section 2.3. In the first layer (Eq. (3)), the deductible level is set so that households will pay for 15% of the total flood damage themselves. The second layer (Eq. (4)) provides coverage through insurance up to a cap that is initially €5 billion. The government covers any remaining damage above the cap (Eq. (5)). Moreover, the flat rate premium for households living on higher lands is set at €50 per year.

Table 8 shows the ability of the insurance fund to pay for the flood damage without creating a negative balance under different combinations of values of the model parameters and scenarios used. The '+' or '−' sign shows whether the combination results in either a positive or negative build up of the insurance fund in any year over a period of 85 years (2015–2100). In this case reserves remain positive under Scenario 1 and the extreme flood Scenario 3. Scenario 2 with several consecutive smaller floods causes slightly negative reserves during the initial stages of the fund. Apparently, a series of several smaller events disturbs the build-up capacity of the insurance fund. This is because the assumed damage in each of the five events in Scenario 2 is below the cap for the insurer, which was set at €5 billion. In the case of these relatively small flood

Table 8
Insurance reserves under three flood scenarios and different combinations of caps and contributions by households in higher regions of the Netherlands. The '+' or '–' sign shows whether the combination results in either a positive or negative build up of the insurance fund in any year over a period of 85 years (2015–2100).

Parameter values in the CRIM model	Flood scenario 1 (2 large river floods)	Flood scenario 2 (5 smaller floods)	Flood scenario 3 (1 extreme storm surge)
Premium high regions €50 per year Cap €5 billion	+	–	+
Premium high regions €10 per year Cap €5 billion	–	–	+
Premium high regions €50 per year Cap €1 billion	+	+	+
Premium high regions €10 per year Cap €1 billion	+	+	+

events, only households and insurers are liable for the damage occurred. Furthermore, simulations show that if the flat-rate premium is lowered to €10 per year for the higher lying regions of the Netherlands, as has been proposed by Kok (2005), then the fund becomes negative in both Scenarios 1 and 2.

When adjusting the cap to €1 billion, the development of the insurance reserves is hardly disturbed under each of the three scenarios. Important, however, is the contribution by households in the high regions of the Netherlands. If this contribution is reduced from €50 per year to €10 per year, then the fund capacity would be between 20% and 45% lower. Furthermore, when testing the layered model using different caps on the insurance layer, it appears that the maximum cap can be about €10 billion without having a negative build-up of the insurance fund under our flood scenarios. The maximum cap, however, with a flat-rate premium of €10 for the higher parts of the country is €1.5 billion, which is remarkably lower. Obviously, the government contribution varies across the different scenarios and modelling assumptions.

An important issue in setting up a new flood insurance scheme is 'timing risk'. Timing risk refers to the possibility that insurers that cover flood risks have to pay large claims before they are able to collect sufficient premiums (Botzen and van den Bergh, 2008). This is especially problematic in the case of private insurance without government coverage of the extreme damage. Timing risk is also an issue in the case of public-private insurance because insurers may have generated insufficient reserves to pay for their share of flood damage during the first years when the insurance is introduced. A solution for this is that the government provides a guarantee to cover damage in case insurers' funds are insufficient in the initial phase of the insurance or to gradually increase the cap level over time.

5. Conclusions

Recently, long-term insurance contracts with a duration of 5, 10 or 15 years have been proposed as a solution for covering flood risk and accommodating increasing flood losses. It has been argued that establishing a long-term relation between the policyholder and the insurance company provides better incentives to reduce risk through undertaking damage mitigation measures. Such improved incentives for flood loss reduction are imperative, given the observed trends in flood losses, and the projected increase in flood risk due to climate change. However, the uncertainty of how future risk will develop as a consequence of climate and socio-economic change may complicate insurers' rate-setting of long-term contracts. This study has examined this issue by estimating the effects of climate and socio-economic change on flood risk and flood insurance premiums of short- and long-term flood insurance contracts in the Netherlands. Important topics for future research are the relation between long-term insurance and mitigation and regulatory issues with such contracts.

A broad range of simulations with hydrological and flood damage models for the Netherlands were used to estimate the future development of flood risk for 53 geographical low-lying dike-ring areas. These calculations were performed for a range of climate-change scenarios of sea-level rise and increases in maximum river discharges, as well as of socio-economic scenarios of economic and population growth, which change land use. The resulting estimates of flood risk are input for the calculations of short- and long-term flood insurance premiums over time under the aforementioned scenarios. Furthermore, this study has explored the dynamics of insurers' funds in the face of several flood scenarios. In particular, the development of insurance funds was examined with a spatial "Climate Risk Insurance Model (CRIM)" for a private insurance arrangement and a 'three-layered' public-private insurance program. These arrangements have been proposed in the Netherlands as alternatives for the current ad hoc government arrangement for compensating flood damage ex post a flood disaster.

The estimation results of the current risk-based flood insurance premiums for 53 dike-ring areas in the Netherlands reveal that large regional differences exist in the premium levels that range in from €1/up to €250 per year. In general, those dike-ring areas with the lowest concentrations of population in combination with a relatively low protection level and high inundation levels have the highest flood risk and premiums. Overall, the future projections of flood insurance premiums show that premiums may increase considerably as a result of socio-economic and climate change, but that the increase is very region specific even in a small country like the Netherlands. The estimation results of flood insurance premiums of long-term insurance contracts with durations of 5, 10 and 15 years reveal fundamental problems with their premium determination in the face of uncertainty about climate and socio-economic change. Our numerical exercise using four scenarios of future risks showed that there is an incentive for either the insurance company or for the consumer to, respectively, market or purchase the short-term contract of 5 years if uncertainty exists about the true trend of climate and socio-economic change. Moreover, the potential effects of climate and socio-economic change on long-term insurance premiums can be large, which could imply that insurers often need to adjust premiums over time. It has been suggested by other studies that the problem of changes in risk can be overcome by allowing for a renegotiation of long-term contracts over time based on new information about changed weather conditions. Our study reveals that, although such an index could be very useful, it seems to be very difficult to construct it, given the large and very regional specific effects that climate change and socio-economic change may have on future risk, while the effects of government climate-change adaptation on flood risk also play a role. Clearly, there is a need for further research to better improve our understanding of how climate and socio-economic change are expected to influence future flood risk before the accurate pricing of long-term flood insurance contracts is feasible.

Given the complications with pricing long-term flood risk, it seems advisable to examine the introduction of one-year flood insurance contracts in the Netherlands, at least until the great uncertainties with climate and socio-economic change on flood risk have been resolved. The estimations performed with the CRIM model indicate that a private insurance fund would have difficulties with building up sufficient financial reserves to pay for flood damage, which was examined for a variety of flood scenarios. The insurance fund of the three-layered insurance arrangement is more stable under the various flood scenarios. When testing the layered model using different caps on the insurance layer, it appears that the maximum cap could be in between €1.5 billion and €10 billion, depending on the contribution of households in higher regions of the Netherlands under the flood scenarios considered here. Future research could in more detail examine the optimal level of the cap considering the capacity of the Dutch insurance sector to cover flood losses and their risk appetite. Our results show that contributions of households in higher regions of the Netherlands could considerably increase the capacity of the insurance fund. Nevertheless, whether this form of solidarity is desirable may be seen as a political decision. Overall, our results show that climate change can have profound effects on flood risk in the Netherlands, which indicates that a debate is in order about who should pay for the projected increase in flood losses, and how to establish an efficient and equitable flood loss compensation arrangement.

Acknowledgements

We are grateful to Howard Kunreuther and Jeroen van den Bergh for their comments and suggestions to improve earlier drafts of this paper. We also thank Philip Bubeck for the damage calculations. This research was conducted as part of the BSIK program Climate Changes Spatial Planning, the NCIP project A9, and has been partly funded by a Veni grant by The Netherlands Organisation for Scientific Research (NWO). We thank the AVV project A13 for sharing data and models. The usual disclaimer applies.

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