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ORIGINAL ARTICLE

# Influence of climate change and socio-economic development on catastrophe insurance: a case study of flood risk scenarios in the Netherlands

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**Abstract** Damage from weather-related events is expected to increase in the future due to socio-economic growth that increases exposure to natural disasters and anticipated climate change. This paper studies the long-term impacts of climate change and land-use planning on flood risk, with a particular focus on flood risk insurance in the Netherlands. This study estimates the full probability distributions of flood damage under four different scenarios of climate change and socio-economic development for the year 2040. Subsequently, the risk-based (re)insurance premiums for flood coverage are estimated for each of the 53 dyke-ring areas in the Netherlands, using a method that takes into account the insurer's risk aversion to covering uncertain catastrophe risk. On the basis of the results, we can draw four main lessons. First, extreme climate change with a high sea level rise has a higher impact on flood (re)insurance premiums compared with future socio-economic development. Second, (re)insuring large flood losses may become very expensive in the future. Third, a public–private insurance system in which the government acts as a risk-neutral reinsurer of last resort, accompanied by comprehensive adaptation and risk reduction measures, could be a good solution for making flood risk insurance available at an affordable price. Fourth, given the projected increase in flood risk, it is especially important that flood insurance contributes to climate change adaptation.

**Keywords** Climate change · Flood insurance · Future scenario · Insurance coverage · Public–private insurance · Risk aversion

## Introduction

Socioeconomic developments, climate change, and related sea level rise are projected to have a large impact on the frequency and severity of floods over time, and, hence, on the financial damage that flooding causes (Botzen et al. 2010; Klijn et al. 2007; Koomen et al. 2008; Ranger and Surminski 2012). Increased weather-related risks may affect the availability of Property and Casualty (P&C) insurance, as a result of the increasing premiums that are required to cover (heightened) risks.

A steady increase in climate-related damage in the past and the projected increase of flood risks have shifted the attention of governments, policy makers, and financial institutions from the prevention of disasters to integrated risk management approaches for catastrophic events, which include adequate loss compensation arrangements (Hall 2003; Merz et al. 2010). Accurate assessments of future flood risks can be helpful to governments and insurers when designing risk mitigation strategies, pricing insurance premiums, and establishing insurance coverage amounts (Aerts and Botzen 2011; Paudel et al. 2013). In the Netherlands, the main focus of the current flood risk management policy is to lower the probability of the flood hazard

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through prevention, while a comprehensive flood insurance system is not available (Aerts and Botzen 2011; Vis et al. 2003). Only a public compensation arrangement (called the "WTS") exists, which provides partial compensation for flood damage in an ad-hoc manner through the Dutch government. However, it has been suggested that flood insurance could be more efficient in compensating flood victims for projected flood damage in the future (Jongejan and Barrieu 2008). This has initiated discussions between the Dutch government and private insurance companies about introducing flood insurance in a public–private (PP) partnership, in which both insurers and the government cover part of the flood damage (Aerts and Botzen 2011; Paudel et al. 2012).

A number of studies have applied a scenario approach to provide insights into the impact of climate, land-use, and demographic changes on future flood damage and the corresponding flood probabilities in the Netherlands (Bouwer et al. 2009, 2010; Kok et al. 2005; Vrijling 2001; Wilby and Harris 2006). Klijn et al. (2007) and Aerts et al. (2008) use several scenarios in order to assess the future impact of socio-economic development and climate change on flood risk for the 53 dyke-ring areas in the Netherlands. Aerts and Botzen (2011) use estimates of future flood risk from the latter project (Aerts et al. 2008)—which is called Aandacht voor Veiligheid (AVV)—for assessing long-term flood insurance premiums under different future scenarios of socio-economic development and climate change. One of the main shortcomings of these studies is that the premium estimates are based on scenarios that are described by a single flood probability, which may fail to capture the full probability distribution of flood damage (Paudel et al. 2014).

The main purpose of this article is to study the long-term effects of climate change and socio-economic development on flood risks, flood (re)insurance premiums, and allocation of damage coverage between the main stakeholders in a PP insurance system in the Netherlands. Contrary to the existing studies, the methodology followed in this paper takes the full probability distribution of flood damage into account for estimating flood (re)insurance premiums in the Netherlands, as described in Paudel et al. (2013, 2014). Paudel et al. (2013, 2014) apply these methods for current flood risks, while this study extends this previous research to scenarios of future risk under climate and socio-economic change. Insights into the potential developments of future flood insurance premiums and the allocation of risk in a PP flood insurance system are important for establishing a flood insurance arrangement that is financially viable, and can cope with future changes in risks.

The remainder of this paper is structured as follows. Section "Methodology" describes the data and the statistical methods. Section "Results and discussion" presents the results of the flood risk estimates and flood insurance premiums for different scenarios of future risk. Section "Discussion" makes policy recommendations. Section "Conclusions and recommendations" concludes.

## Methodology

### Study area

The low-lying areas of the Netherlands are divided in 53 dyke-ring areas that each have their own protection system and safety standard. This study will discuss the results of three dyke-ring areas—7, 14, and 36—in detail because these areas are assumed to be roughly representative for the remaining dyke-ring areas. The flood probabilities of each of these 53 dyke rings are based on a safety standard, which has been defined at a level between 1/10,000, and 1/1,250 in the "Water Embankment Act,"' and the potential damage is related to the economic value located within these areas. This study makes projections of the probability distributions of flood damage for the year 2040 and estimates their impact on the associated (re)insurance premium for all 53 dyke-ring areas.

### Overview of the overall methodological framework

The conceptual view in Fig. 1 provides an overview of the main methodological steps followed in this paper. The estimation method consists of the following three main parts: the estimation of probability distributions of flood damage in the current situation (in terms of safety standards and exposed assets) using the method by Paudel et al. (2013) (see Part I, Sect. "Flood damage estimation for the year 2015" of this present paper); the use of future information on socio-economic development and climate change from Aerts et al. (2008) and Aerts and Botzen (2011) in order to make projections of flood risks (see Part II, Sects. "Climate change impacts on flood probabilities"–"Future projections of stochastic flood damage" of this present paper); and the application of the method in Paudel et al. (2014) to estimate flood insurance premiums (see Part III, Sect. "The estimation of flood insurance premiums" of this present paper).

#### *Flood damage estimation for the year 2015*

This paper uses the stochastic estimates of flood damage from Paudel et al. (2013) as a starting point to create probabilistic projections of flood damage by the year 2040. Paudel et al. (2013) use Bayesian Inference (BI) and the Monte Carlo technique to estimate the probability distribution of flood damage for each of the 53 dyke-ring areas

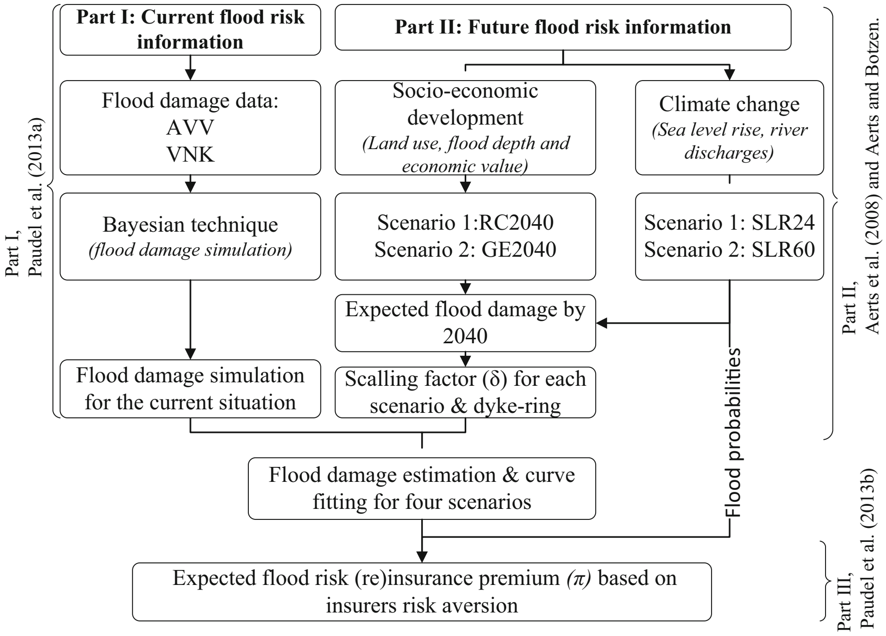


**Fig. 1** Overview of the methodology. *Note*: The Veiligheid Nederland in Kaart (VNK) and Aandacht Voor Veiligheid (AVV) are two major studies of flood risk in the Netherlands

by simulating flood events for 250,000 return periods, in which flooding occurs under the assumption of no correlation of flood events between dyke rings. The input data used by Paudel et al. (2013) are the flood damage estimates from the research programmes VNK and AVV. The current probability distributions of flood damage are multiplied by the scaling factor ($\delta$) to estimate the future distributions for the year 2040. The scaling factors ($\delta$) per dyke-ring area are derived from Aerts et al. (2008) and Aerts and Botzen (2011) (see Sects. "Climate change impacts on flood probabilities"–"Future projections of stochastic flood damage" of this present paper).

### *Climate change impacts on flood probabilities*

Future flood probabilities are assumed to change due to sea level rise (SLR) and river water discharges from the rivers Rhine and Meuse (Aerts et al. 2008). The maximum discharges in the current situation for, respectively, the rivers Rhine and Meuse are 4,150 and 16,000 cubic meters per second ($m^3/s$), which climate change is expected to increase to, respectively, 4,600 and 18,000 $m^3/s$(Aerts et al. 2006). SLR is either 24 or 60 cm. The projection of the 24 cm SLR (CC24) relates to low sea level rise sensitivity, which corresponds to an increase in global temperature by 1 °C in 2050. The 60 cm SLR (CC60) indicates a high sea level rise sensitivity and corresponds to an increase in global mean temperature of 2 °C by 2100 and similar increases in peak river discharges as the 24 cm SLR scenario (van den Hurk et al. 2006). Table Online Resources (OR) 1 shows flood exceedance probabilities under different climate change scenarios, as have been derived by Aerts and Botzen (2011).

### *Socio-economic change and flood damage estimation*

The flood damage projections for the years 2040 and 2100, corresponding to the exceedance probabilities, as shown in OR 1, and socio-economic development, are derived from Aerts et al. (2008) and Aerts and Botzen (2011). The socio-economic scenarios represent the spatial land-use changes and socio-economic growth for the year 2040 in the Netherlands and are labeled as Regional Communities (RC) and Global Economy (GE) (Janssen et al. 2006). GE is a scenario with a strong population and economic growth and increase in buildings, accompanied by strong international economic integration. In contrast, RC is a stable socio-economic scenario, with slow economic and population growth.

In order to analyze sensitivity to climate change of future flood damage and the corresponding flood insurance premiums, two additional projections are developed for the year 2040 that correspond to a 60 cm SLR and both the GE and RC scenarios (Janssen et al. 2006). Compared with the four main scenarios for SLR presented in the IPCC WGII AR5 2014 report (RPC2.6, RPC2.5, RPC6.0, and RPC8.5), the 60 cm SLR by 2040 used in this manuscript is a higher end scenario. To derive these additional projections, an exponential regression is applied to the existing data from Aerts et al. (2008) (See Eq.1). The corresponding equation for each dyke-ring area, $j = 1, \ldots 53$, can be given as:

$$E[Y]^j = a^j e^{q^j * m^j}, \quad (1)$$

where $E[Y]^j$ (the dependent variable) represents the projections of average future flood damage from Aerts et al. (2008) with respect to the SLR variable $q^j$(the independent variable), and the unknown coefficients of the slope $m^j$ and the intercept $a^j$. OR 4 provides the estimated slopes and intercepts, which are used to create projections of future flood damage with 60 cm SLR, and the corresponding flood damage estimate per dyke-ring area.

### Future projections of stochastic flood damage

This study uses the probabilistic estimates of average flood damage made by Paudel et al. (2013) for the current situation (see Part I, Fig. 1 of the present paper), which are approximately 49 % lower compared with AVV average damage. This difference is mainly caused by the use of the full probability density of flood damage by Paudel et al. (2013), which also includes damage from events other than only extreme dyke overtopping, which was used for deriving AVV damage estimates.

In particular, to project flood damage under four scenarios for the year 2040, the simulated flood damage for 2015 from Paudel et al. (2013) is scaled by the factor $\delta$ (see Eq. 3 below). This factor is estimated as the ratio between the projections of flood damage for 2040 for two different heights of SLR (24 and 85 cm) and the damage estimates for 2015 from Aerts et al. (2008) (see Sect. "Climate change impacts on flood probabilities" and OR 3). Let the $X^j = x_1^j, \ldots, x_{250{,}000}^j$ be a stochastic vector of flood damage vector obtained from the 250,000 flood damage simulations made by Paudel et al. (2013) for dyke-ring area $j$, with $j = 1, \ldots, 53$. The projections of future stochastic damage $(\widehat{X}_i^j)$ for scenario $i$, with $i = 1, 2, 3, 4$, are approximated by:

$$\widehat{X}_i^j = X_{2015}^j * \delta_i^j \tag{2}$$

where $X_{2015}^j$ is the stochastic flood damage vector for the year 2015, which is obtained using Monte Carlo simulations, following the methodology described by Paudel et al. (2013); $\delta_i^j$ is the scaling factor for dyke-ring area $j$ (see Sect. "Climate change impacts on flood probabilities" above) and scenario $i$, with $i = 1, 2, 3, 4$. The scaling factor $\delta$ is estimated as:

$$\delta_i^j = \left(E\left[Y_i^j\right]\right)/E\left[Y_{2015}^j\right] \tag{3}$$

where $(E[Y_i^j])$ represents the average flood damage for the dyke-ring area $j$ and scenario $i$, and $E[Y_{2015}^j]$ stands for the average flood damage amount for the current situation (see OR 5).

### The estimation of flood insurance premiums

The updated damage projections from Sect. "Future projections of stochastic flood damage" are now used to derive expected flood damage under each scenario and to estimate the (re)insurance premiums according to the methodology that is described in detail by Paudel et al. (2014). Here, we provide a brief summary of this method. Figure 2 depicts a cumulative distribution function, $F(x)$ of flood damage $x$, for an insurance system with two (insured and insurer only) or three layer, in which the insured, the insurer, and the reinsurer or government participate. It is assumed that the potential maximum damage cannot exceed the amount $T$. The insured and the insurer can choose individual retention levels equal to, respectively, D (deductible) and M (stop-loss). Deductible and stop-loss refer to out-of-pocket expenses that must be paid by, respectively, a policyholder (insured) and insurer before corresponding insurer and reinsurance will pay any damage. Unless stated otherwise, the results in this paper are based on deductible and stop-loss amounts of 15 and 84 %, respectively. Moreover, premiums are estimated for two types of insurance systems: namely two-layer and three-layer systems. In a two-layer insurance system, no reinsurer is involved, and the insured amount is equal to 99.9 % of the TVaR amount ($v$), which is also called the required maximum insurance coverage (RMIC) shown in OR 6. TVaR is defined as the expected damage in the worst $\alpha$ percent of the cases (see Paudel et al. (2014)). In a three-layer system, the insurer pays a reinsurance premium in exchange for a reinsurance amount equal to 99.9 % of the TVaR amount, which is also indicated by the required maximum reinsurance coverage (RMRC). Usually, only some areas can flood, depending on the event, meaning that the insurance spreads flood risks across households in a region. Theoretically, flood losses with a devastating effect are also conceivable, in which the total damage can even exceed the total amount of insurers' resources. In such cases, it would be unrealistic to assume that all losses are insurable.

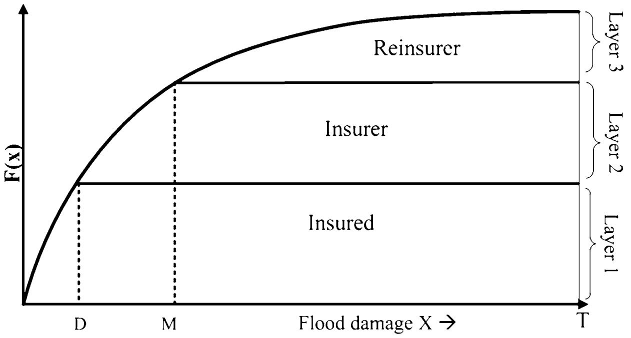


**Fig. 2** A conceptual model of a cumulative loss function with three layers of own risk for the insured, the insurer, and the reinsurer

Therefore, it is assumed that the damage outliers above 99.9 % of the TVaR threshold are not insured, as these are generally too expensive and may require a very high premium.

Studies show that the flood insurance premium to be paid can vary significantly based on whether the (re)insurance is provided by either a risk-averse (RA) or a risk-neutral (RN) agency (Bernard and Tian 2009; Paudel et al. 2014). In general, commercial insurance companies demand an extra surcharge on the premium as compensation for covering highly uncertain large potential losses. A government has different interests and responsibilities, and may act as a last resort for catastrophe risk. In this respect, it is common to assume that the government is an RN agency. Involvement of an RN agency would lead to lower premiums, making an insurance system more feasible from an insurance perspective and affordable for property owners. This paper estimates flood insurance premiums for two categories of insurer risk attitudes: (1) both private insurers and reinsurers are RA; (2) a RN government acts as a reinsurer, and the private insurer is also risk neutral (RN). The government charges a risk-neutral reinsurance premium for the provided reinsurance coverage. The mathematical functions and derivations of (re)insurance premiums, deductible (*D*), and stop-loss amounts (*M*) are discussed in Paudel et al. (2014). Average flood insurance premiums per homeowner are calculated by dividing flood risk for households by the number of houses in a dyke-ring area. The future building stock differs between the RC and GE scenarios (OR 7).

## Results and discussion

### Flood damage results

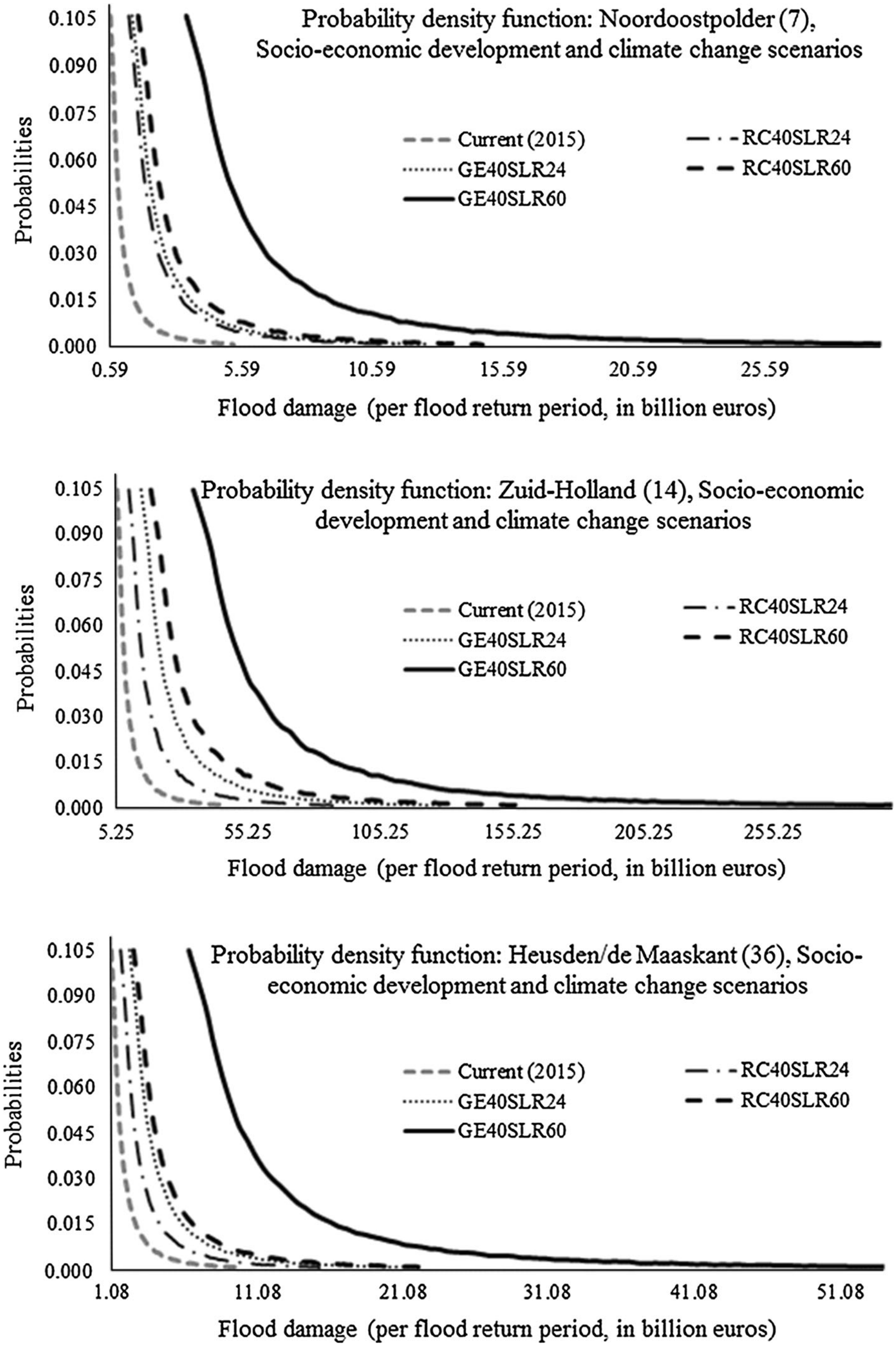
The detailed results are provided here for the following three representative dyke-ring areas: the Noordoostpolder (7), Zuid-Holland (14), and Land van Heusden/de Maaskant (36). These 3 dyke-ring areas share similar geographical features and a common flood probability with three main classes of dyke-ring areas in the Netherlands: namely intertidal areas, coastal areas, and areas vulnerable to river flooding. Dyke-ring Noordoostpolder can be representative for the majority of dyke-ring areas, which have a flood probability of about 1/4,000 per year. Dyke-ring Zuid-Holland (along with Noord-Holland) is one of the dyke rings with the lowest flood probability in the Netherlands of about 1/10,000 per year. This dyke-ring is located along the densely populated coastline and has a high concentration of property values. Dyke-ring 36, Land van Heusden/De Maaskant, shares similar features with the majority of the river dyke-ring areas, which have a higher flood probability of about 1/1,250 per year (Bouwer et al. 2010).

Figure 3 shows the probability density functions of flood damage for the three dyke-ring areas. They provide an indication of potential flood damage under a specific climate change and socio-economic scenario, as well as for the current situation. The probabilities of observing a specific damage amount conditional on a flood happening are shown on the vertical axis, while the corresponding damage (in billion €) is displayed on the horizontal axis. It should be realized that these density functions do not yet incorporate the potential effects of climate change on the probability of flooding, which are accounted for in the estimation of flood insurance premiums in Sect. "Insurance premiums" below. The density functions indicate that most of the damage for each dyke-ring area is concentrated on the left side of the curve, although the extent of this concentration clearly differs between individual dyke-ring areas and the future scenarios. As an illustration, the statistical mean for all the three flood density functions in the current situation is located around the 67.9 data percentile, while this mean clearly shifts to the right under the four future scenarios. As expected, this suggests that large losses will occur more frequently as a result of climate change. The annual minimum flood damage under each scenario will also increase. The future projections of expected flood damage corresponding to the GE40SLR60 and the RC40SLR60 scenarios are, respectively, the highest and the second highest for all of the three dyke-ring areas. High economic growth and a high SLR are the main reasons for this substantial increase in flood risk estimates. OR 8 shows flood damage estimates for each dyke-ring area in the current situation and the year 2040 per flood return period.

### Insurance premiums

Table 1 provides an overview of the total annual RA and RN flood insurance premiums per scenario, to be paid by individual homeowners within a specific dyke-ring area. The future premiums reflect the combined effects of socio-economic and climate change on flood damage as well as the effect of climate change on the flood probability. Columns 2 and 3 show estimates of annual RA and RN insurance premiums for the current situation, while the remaining last eight columns provide an indication of the projected future increase in RA and RN premiums with respect to the current amounts. This difference arises mainly because the RA premiums include a surcharge that reflects the rate of insurers' risk aversion against catastrophe risk that is dependent on the risk variance of flood losses (see Paudel et al. 2014). Dyke-ring 6 with an RA premium of €0.3 is the cheapest area to purchase flood

**Fig. 3** Flood damage density functions for the current situation and for the year 2040 under the GE and RC socio-economic growth scenarios and sea level rise of 24 or 60 cm (dyke-ring area 7, 14 and 36). *Note*: The probability is the probability of a flood damage amount conditional on a flood happening



insurance, while dyke-ring 16 with an RA premium of €338 is the most expensive area. The flood damage relative to the number of houses within the related dyke-ring area is the main explanation for this large difference (see OR 7). Because the average premium estimates are per dyke-ring area, a relatively large number of houses in a certain dyke-ring area compared with the potential flood damage result in a lower collective premium for homeowners. The current RA insurance premiums are approximately 161 % of the current RN premiums, while in general this difference becomes larger under the four future scenarios. This has been caused by the increasing premium surcharge for insurer's risk aversion to catastrophe risk for large losses, which depends on the loss variance that monotonically increases with large losses. Compared with the current RA premiums, RA insurance premiums that correspond to a 60 cm SLR are much higher than those corresponding to a 24 cm SLR. For example, the approximated RA premiums for dyke-ring 14 under the RC40SLR60 and GE40SLR60 scenarios are, respectively, 28 and 32 times higher than the

**Table 1** Overview of annual risk-averse (RA) and risk-neutral (RN) flood insurance premiums (in €) corresponding to the current and the four combined climate and socio-economic change scenarios

| Dyke | Current | | RC40SLR24 | | RC40SLR60 | | GE40SLR24 | | GE40SLR60 | |
|---|---|---|---|---|---|---|---|---|---|---|
| Nr. | RA | RN | RA | RN | RA | RN | RA | RN | RA | RN |
| 6 | 0.3 | 0.2 | 2.6 | 1.2 | 11 | 2.3 | 2.5 | 1.5 | 14 | 2.2 |
| 13 | 5 | 3 | 22 | 13 | 124 | 48 | 32 | 19 | 180 | 36 |
| 14 | 6 | 4 | 25 | 15 | 166 | 42 | 36 | 21 | 191 | 32 |
| 44 | 11 | 7 | 31 | 20 | 121 | 40 | 52 | 28 | 164 | 29 |
| 47 | 12 | 7 | 23 | 25 | 133 | 61 | 38 | 35 | 135 | 50 |
| 32 | 12 | 7 | 49 | 32 | 286 | 115 | 59 | 46 | 403 | 97 |
| 34 | 13 | 8 | 84 | 19 | 305 | 55 | 108 | 31 | 538 | 51 |
| 17 | 14 | 9 | 34 | 26 | 224 | 105 | 49 | 37 | 305 | 82 |
| 8 | 17 | 10 | 33 | 19 | 226 | 60 | 44 | 27 | 305 | 56 |
| 36 | 22 | 13 | 88 | 66 | 812 | 373 | 128 | 94 | 1,965 | 367 |
| 7 | 22 | 13 | 50 | 25 | 238 | 76 | 55 | 36 | 422 | 80 |
| 18 | 25 | 15 | 71 | 42 | 237 | 90 | 80 | 60 | 283 | 71 |
| 19 | 26 | 15 | 70 | 42 | 248 | 91 | 66 | 61 | 253 | 77 |
| 46 | 26 | 16 | 59 | 29 | 1,208 | 111 | 107 | 42 | 1,118 | 102 |
| 21 | 29 | 17 | 164 | 70 | 1,399 | 412 | 174 | 101 | 1,915 | 324 |
| 45 | 29 | 18 | 81 | 61 | 298 | 155 | 109 | 89 | 384 | 123 |
| 11 | 34 | 20 | 130 | 97 | 1,682 | 512 | 209 | 140 | 1,922 | 405 |
| 35 | 34 | 21 | 244 | 141 | 782 | 292 | 278 | 189 | 1,132 | 180 |
| 4 | 34 | 21 | 263 | 146 | 1,379 | 296 | 270 | 147 | 1,589 | 190 |
| 49 | 49 | 30 | 186 | 110 | 616 | 305 | 171 | 159 | 709 | 249 |
| 15 | 51 | 30 | 306 | 182 | 2,975 | 1,034 | 346 | 261 | 3,104 | 816 |
| 48 | 61 | 37 | 227 | 164 | 1,069 | 517 | 362 | 236 | 1,672 | 394 |
| 1 | 67 | 40 | 377 | 229 | 2,904 | 969 | 384 | 329 | 3,543 | 996 |
| 52 | 69 | 41 | 247 | 155 | 898 | 436 | 309 | 223 | 1,307 | 339 |
| 12 | 69 | 41 | 447 | 219 | 2,825 | 1,080 | 539 | 220 | 3,903 | 424 |
| 10 | 71 | 42 | 364 | 215 | 2,862 | 1,097 | 415 | 309 | 3,640 | 879 |
| 9 | 75 | 45 | 176 | 85 | 1,853 | 317 | 248 | 122 | 4,012 | 404 |
| 41 | 75 | 45 | 325 | 228 | 2,576 | 1,181 | 520 | 328 | 3,798 | 894 |
| 25 | 76 | 46 | 570 | 190 | 2,658 | 621 | 1,185 | 274 | 5,088 | 391 |
| 28 | 78 | 47 | 393 | 207 | 2,241 | 738 | 427 | 297 | 2,663 | 587 |
| 5 | 79 | 48 | 431 | 271 | 3,251 | 1,156 | 406 | 390 | 4,598 | 1,304 |
| 2 | 82 | 49 | 411 | 280 | 3,689 | 1,246 | 453 | 403 | 4,121 | 1,225 |
| 42 | 85 | 51 | 321 | 199 | 1,039 | 541 | 319 | 287 | 1,375 | 442 |
| 51 | 91 | 55 | 334 | 206 | 1,699 | 588 | 560 | 297 | 1,982 | 445 |
| 3 | 91 | 55 | 388 | 243 | 2,230 | 712 | 392 | 350 | 2,556 | 735 |
| 27 | 94 | 56 | 414 | 249 | 2,323 | 891 | 456 | 359 | 3,003 | 739 |
| 22 | 100 | 60 | 307 | 226 | 2,933 | 1,125 | 563 | 325 | 3,983 | 836 |
| 24 | 103 | 62 | 687 | 362 | 3,970 | 1,601 | 876 | 628 | 5,310 | 782 |
| 29 | 107 | 64 | 334 | 283 | 2,511 | 1,013 | 486 | 408 | 3,107 | 841 |
| 26 | 112 | 67 | 576 | 296 | 3,069 | 1,059 | 617 | 427 | 4,180 | 865 |
| 30 | 117 | 70 | 536 | 312 | 3,721 | 1,113 | 923 | 448 | 5,283 | 809 |
| 50 | 120 | 72 | 356 | 273 | 1,512 | 778 | 398 | 393 | 1,667 | 643 |
| 39 | 148 | 89 | 1,301 | 451 | 7,049 | 2,416 | 644 | 650 | 4,913 | 2,004 |
| 33 | 151 | 91 | 407 | 171 | 1,982 | 554 | 449 | 246 | 2,419 | 416 |
| 38 | 157 | 95 | 712 | 448 | 5,045 | 2,562 | 977 | 645 | 8,239 | 1,955 |
| 20 | 168 | 101 | 670 | 422 | 3,317 | 1,375 | 931 | 605 | 4,917 | 1,057 |

**Table 1** continued

| Dyke | Current | | RC40SLR24 | | RC40SLR60 | | GE40SLR24 | | GE40SLR60 | |
|---|---|---|---|---|---|---|---|---|---|---|
| Nr. | RA | RN | RA | RN | RA | RN | RA | RN | RA | RN |
| 40 | 182 | 110 | 1,151 | 556 | 6,578 | 2,954 | 795 | 800 | 6,399 | 2,456 |
| 53 | 190 | 114 | 627 | 429 | 2,848 | 1,210 | 688 | 618 | 3,646 | 1,035 |
| 43 | 198 | 119 | 709 | 461 | 2,592 | 1,254 | 1,111 | 663 | 4,311 | 937 |
| 37 | 209 | 126 | 1,064 | 595 | 8,822 | 3,749 | 1,106 | 856 | 12,032 | 3,034 |
| 31 | 221 | 133 | 1,063 | 588 | 5,915 | 2,102 | 2,082 | 847 | 15,264 | 1,626 |
| 23 | 272 | 164 | 839 | 617 | 8,009 | 3,073 | 1,539 | 887 | 10,883 | 2,283 |
| 16 | 338 | 203 | 1,375 | 803 | 6,415 | 2,566 | 1,557 | 1,152 | 8,100 | 2,025 |
| Average | 85 | 51 | 380 | 236 | 2,448 | 963 | 484 | 239 | 3,757 | 873 |

Premiums are based on the 15 % deductible level (see OR 6 for the corresponding RMIC amounts)

current RA amounts. However, the premiums associated with the scenarios RC40SLR24 and GE40SLR24 are much lower: namely 5 and 6 times the current RA amounts, respectively. This indicates that a high SLR will lead to an exponential increase in insurance premiums making flood risk hardly insurable. Contrast to the RA insurance premiums, the RN estimates for the scenarios RC40SLR24, RC40SLR60, GE40SLR24, and GE40SLR60 are, respectively, 4, 13, 5, and 13 times the current RN premiums. The last row in Table 1 depicts the collective amounts of the average premiums for all 53 dyke-ring areas. These are lower than the premiums for the last 19 dyke-ring areas.

### Reinsurance premiums

Table 2 provides an overview of expected annual RA and RN reinsurance premiums per scenario to be paid by the insurer to the reinsurer. Similar to the primary insurance premiums in the previous Section, dyke-ring 6 has the lowest reinsurance premium of €0.2, while dyke-ring 16 has the most expensive premium with a reinsurance premium of €187. The average current RA reinsurance premiums for dyke-ring 14 are about 2.5 times the RN amounts. This indicates that the reinsurer requires a higher surcharge on premiums compared with the primary insurer for which the relationship between RA and RN premiums is about 1.66 (see Sect. "Insurance premiums"). This is consistent with practice, because usually reinsurers provide coverage to losses that are very uncertain, for which they demand an additional premium surcharge (Kunreuther and Michel-Kerjan 2011). The difference between the RA and RN reinsurance premiums becomes larger for larger losses. This is even more evident for the reinsurance premiums belonging to the scenarios with a 60 cm SLR. This implies that a higher SLR will result in a higher reinsurance premium, making reinsurance more expensive. The RA reinsurance premiums for dyke-ring 14 under the RC40SLR60 and GE40SLR60 scenarios are, respectively, 27 and 31 times the current RA amounts, while this difference for the corresponding RN premiums is only 19 and 21 times the current amounts. The last row in Table 2 shows the approximated average RA and RN reinsurance premium per homeowner collectively for all 53 dyke-ring areas, which is lower than the average amounts for the last 21 individual dyke-ring areas.

## Discussion

The estimates of flooding and the corresponding (re)insurance premiums presented in the results will be discussed in this section with respect to the following three main aspects: the impact of climate change and socio-economic development on flood risk in the future; the difference in the RA and RN (re)insurance premiums; and the main implications of the results for flood risk insurability.

### Impact of climate change and socio-economic development on flood risk

Our results show that extreme climate change with a high SLR can considerably increase flood probabilities, which can cause a large increase in flood insurance premiums in low-lying areas in the Netherlands. Already, the independent effects of socio-economic change and SLR on expected flood damage can be very large. In addition, if the effects of climate change on flood probabilities are taken into account, then the climate change scenarios of 24 and 60 cm SLR could, respectively, increase flood risk by 3 and 14 times the current risk level. The clear shift of flood density functions to the right, which causes thicker and longer tails in Fig. 3, confirms that flood insurance under a high climate change scenario with 60 cm of SLR will be hardly affordable for individual homeowners (Botzen and Van Den Bergh 2012). The expected annual flood damage,

**Table 2** Overview of annual risk-averse (RA) and risk-neutral (RN) flood reinsurance premiums (in €) corresponding to the current and the four combined climate and socio-economic scenarios

| Dyke | Current | | RC40SLR24 | | RC40SLR60 | | GE40SLR24 | | GE40SLR60 | |
|---|---|---|---|---|---|---|---|---|---|---|
| Nr. | RA | RN | RA | RN | RA | RN | RA | RN | RA | RN |
| 6 | 0.2 | 0.1 | 1.2 | 0.6 | 13.2 | 2.6 | 1.4 | 0.8 | 19.9 | 2.9 |
| 13 | 3 | 1 | 12 | 7 | 68 | 26 | 17 | 11 | 99 | 20 |
| 14 | 4 | 1 | 14 | 8 | 92 | 23 | 20 | 12 | 106 | 18 |
| 44 | 6 | 2 | 17 | 11 | 67 | 22 | 29 | 16 | 91 | 16 |
| 47 | 6 | 3 | 13 | 14 | 73 | 34 | 21 | 19 | 75 | 28 |
| 32 | 7 | 3 | 27 | 18 | 158 | 64 | 33 | 26 | 223 | 54 |
| 34 | 7 | 3 | 71 | 16 | 441 | 80 | 82 | 23 | 545 | 52 |
| 17 | 8 | 3 | 19 | 14 | 124 | 58 | 27 | 21 | 169 | 45 |
| 8 | 9 | 4 | 18 | 10 | 125 | 33 | 24 | 15 | 169 | 31 |
| 36 | 12 | 5 | 49 | 36 | 449 | 206 | 71 | 52 | 1,087 | 203 |
| 7 | 12 | 5 | 28 | 14 | 131 | 42 | 30 | 20 | 233 | 44 |
| 18 | 14 | 6 | 40 | 23 | 131 | 50 | 44 | 33 | 156 | 39 |
| 19 | 14 | 6 | 39 | 23 | 137 | 51 | 37 | 34 | 140 | 43 |
| 46 | 14 | 6 | 33 | 16 | 668 | 61 | 59 | 24 | 619 | 56 |
| 21 | 16 | 6 | 91 | 39 | 774 | 228 | 96 | 56 | 1,060 | 179 |
| 45 | 16 | 7 | 45 | 34 | 165 | 85 | 61 | 49 | 213 | 68 |
| 11 | 19 | 7 | 72 | 54 | 930 | 283 | 116 | 78 | 1,063 | 224 |
| 35 | 19 | 8 | 117 | 68 | 1,247 | 465 | 143 | 98 | 3,164 | 503 |
| 4 | 19 | 8 | 116 | 65 | 1,504 | 322 | 287 | 93 | 1,926 | 230 |
| 49 | 27 | 11 | 103 | 61 | 341 | 169 | 94 | 88 | 392 | 138 |
| 15 | 28 | 11 | 169 | 101 | 1,646 | 572 | 192 | 145 | 1,717 | 452 |
| 48 | 34 | 14 | 125 | 91 | 591 | 286 | 200 | 131 | 925 | 218 |
| 1 | 37 | 15 | 209 | 126 | 1,607 | 536 | 213 | 182 | 1,960 | 551 |
| 52 | 38 | 15 | 137 | 86 | 497 | 241 | 171 | 123 | 723 | 188 |
| 12 | 38 | 15 | 265 | 130 | 1,788 | 683 | 504 | 187 | 4,394 | 477 |
| 10 | 39 | 16 | 202 | 119 | 1,584 | 607 | 230 | 171 | 2,014 | 486 |
| 9 | 41 | 17 | 97 | 47 | 1,025 | 175 | 137 | 67 | 2,220 | 224 |
| 41 | 41 | 17 | 180 | 126 | 1,425 | 653 | 287 | 182 | 2,101 | 494 |
| 25 | 42 | 17 | 315 | 105 | 1,470 | 344 | 655 | 151 | 2,814 | 216 |
| 28 | 43 | 17 | 217 | 114 | 1,240 | 408 | 236 | 164 | 1,473 | 324 |
| 5 | 44 | 18 | 238 | 150 | 1,799 | 640 | 224 | 216 | 2,544 | 721 |
| 2 | 45 | 18 | 227 | 155 | 2,041 | 689 | 251 | 223 | 2,280 | 678 |
| 42 | 47 | 19 | 178 | 110 | 575 | 299 | 176 | 159 | 761 | 245 |
| 51 | 50 | 20 | 185 | 114 | 940 | 325 | 310 | 164 | 1,096 | 246 |
| 3 | 51 | 20 | 215 | 134 | 1,234 | 394 | 217 | 194 | 1,414 | 407 |
| 27 | 52 | 21 | 229 | 138 | 1,285 | 493 | 252 | 198 | 1,661 | 409 |
| 22 | 55 | 22 | 170 | 125 | 1,623 | 622 | 312 | 180 | 2,203 | 462 |
| 24 | 57 | 23 | 387 | 204 | 3,371 | 1,359 | 411 | 294 | 13,564 | 1,997 |
| 29 | 59 | 24 | 185 | 157 | 1,389 | 561 | 269 | 226 | 1,719 | 465 |
| 26 | 62 | 25 | 318 | 164 | 1,698 | 586 | 341 | 236 | 2,313 | 479 |
| 30 | 65 | 26 | 296 | 172 | 2,058 | 616 | 511 | 248 | 2,922 | 448 |
| 50 | 66 | 27 | 197 | 151 | 837 | 430 | 220 | 218 | 922 | 356 |
| 39 | 82 | 33 | 719 | 250 | 3,899 | 1,336 | 356 | 360 | 2,718 | 1,109 |
| 33 | 83 | 34 | 225 | 95 | 1,096 | 307 | 248 | 136 | 1,338 | 230 |
| 38 | 87 | 35 | 394 | 248 | 2,791 | 1,418 | 540 | 357 | 4,558 | 1,082 |
| 20 | 93 | 37 | 371 | 233 | 1,835 | 761 | 515 | 335 | 2,720 | 585 |

**Table 2** continued

| Dyke | Current | | RC40SLR24 | | RC40SLR60 | | GE40SLR24 | | GE40SLR60 | |
|---|---|---|---|---|---|---|---|---|---|---|
| Nr. | RA | RN | RA | RN | RA | RN | RA | RN | RA | RN |
| 40 | 101 | 41 | 637 | 307 | 3,639 | 1,634 | 440 | 442 | 3,540 | 1,358 |
| 53 | 105 | 42 | 347 | 237 | 1,576 | 669 | 381 | 342 | 2,017 | 573 |
| 43 | 110 | 44 | 392 | 255 | 1,434 | 694 | 615 | 367 | 2,385 | 518 |
| 37 | 116 | 47 | 589 | 329 | 4,880 | 2,074 | 612 | 474 | 6,656 | 1,678 |
| 31 | 123 | 49 | 588 | 325 | 3,272 | 1,163 | 1,152 | 468 | 8,445 | 899 |
| 23 | 151 | 61 | 464 | 341 | 4,431 | 1,700 | 852 | 491 | 6,021 | 1,263 |
| 16 | 187 | 75 | 761 | 444 | 3,549 | 1,420 | 862 | 637 | 4,481 | 1,120 |
| Average | 47 | 19 | 210 | 131 | 1,354 | 533 | 268 | 132 | 2,079 | 483 |

Premiums are based on the 15 % deductible and 84 % stop-loss levels (see OR 9 for the corresponding RMRC amounts)

which can be derived by dividing the damage estimates per dyke-ring area with the corresponding return periods and taking their average, for all 53 dyke-ring areas altogether is approximately €58 million in the current situation. This is expected to increase to about €1.6 and €2.9 billion, respectively, if the SLR by 24 and 60 cm under the GE scenario. Damage estimates under the GE and RC scenarios with the same SLR show a relatively small difference compared with the estimates for the scenarios with a different SLR. This implies that climate change has a larger impact on projected damage than either level of socio-economic development. An analysis of the relationship between the expected damage amounts in Table OR 8 and the corresponding scaling factors in OR 5 shows that the impact of socio-economic development under the given scenarios will not be more than 2–6 % of the total damage. Our findings that the impact of climate change with a high SLR on future flood damage is larger than it is with either level of socio-economic development are in line with Aerts and Botzen (2011), te Linde et al. (2011), and Bouwer et al. (2010), albeit at different magnitudes. The damage estimates by Aerts and Botzen (2011) under the RC and GE scenarios with 24 cm SLR for 2040 are, respectively, 1.95 and 2.57 times the current estimates, while our results under the similar scenarios are slightly higher: namely 2.05 and 2.61 times the current amounts. Te Linde et al.'s study (2011), which was performed under four different combination of socioeconomic and climate change scenarios, estimates current and future fluvial flood risk by 2030 along the Rhine basin, under the assumption that the current trend of temperature rise continues in the future. They found that the potential effects of climate change on flood risk will be significantly larger than the effects of socio-economic change. According to te Linde et al. (2011), approximately three-quarters of the total impact on potential flood damage by 2030 can be attributed to climate change (te Linde et al. 2011). In addition, a study by Bouwer et al. (2010) about the impact of climate change on potential flood damage for dyke-ring 36 in 2040 finds a slightly higher impact of climate change than either level of socio-economic development. However, the same study shows that the impact of socio-economic change will be higher when certain adaptation (flood prevention) measures are taken (Bouwer et al. 2010).

### Differences between the RA and the RN (re)insurance premiums

In general, the estimated flood (re)insurance premiums show a similar trend to that of expected flood damage; the more extreme the climate change scenario with a high SLR, the higher the (re)insurance premiums. However, the difference between the premiums under the two different climate change scenarios is larger compared with the corresponding damage amounts. This is because the premiums are annual amounts and, thus, are adjusted for the effects of climate change on the actual flood return periods, while this is not the case for the expected flood damage. Moreover, premiums increase more than annual expected flood risk because of an extra surcharge, which is included in the premium through the insurer's risk aversion rate that depends on the risk variance. This reflects the common practice that commercial (re)insurance companies demand an additional premium surcharge for covering extremely large and highly uncertain losses, like flood damage. This additional surcharge for the reinsurance premium will be comparatively higher than for primary insurance premiums because the loss data located on the right-tail of the damage density functions that are typically covered by reinsurance are more dispersed, which leads to a higher rate of risk aversion owing to the higher risk variance. However, if (re)insurance is provided by an RN agency, like the government, this extra surcharge can be omitted and the premium can be kept as low as the expected damage amount (Froot 2001; Paudel et al. 2012). In addition to risk aversion, a part of the difference in premiums between dyke rings is caused by the specific features of the individual dyke-ring areas, such as their geographical position and safety standards, number of houses, impact of climate change on flood probabilities, and expected economic growth in the future. On average, the RA insurance and reinsurance premiums under the GE scenario with a 60 cm SLR are approximately, respectively, 37 and 48 times their current RA amounts. This difference varies between 20 and 60 times the current RA amounts for the individual dyke-ring areas.

The question may arise whether flood risk insurance will be feasible if an extreme climate change scenario with a high SLR, such as 60 cm, becomes the reality. As this may lead to a substantial increase in (re)insurance premiums, affordability and the willingness to pay (WTP) of homeowners may be too low. Botzen and van den Bergh (2012) estimate WTP for flood insurance in the Netherlands by implementing a choice experiment with different flood insurance options among 1,200 homeowners in the river delta. Their results show that the average WTP for flood insurance in the current situation of flood risk in the Netherlands is about €250 per year. This amount is higher than our estimate of the collective average RA premium for the current situation, which is about €85. Botzen and van den Bergh (2012) also estimate how WTP for flood insurance increases if climate change increases flood probabilities, by eliciting flood insurance demand under scenarios of increased flood risk. Their results show that a doubling of the flood probability will lead to an increase in WTP by 16 %, which gives an adjusted amount of about €290 (Botzen and Van Den Bergh 2012). This increase in WTP for flood insurance is much lower compared with the potential increase in flood insurance premiums found in our study, which shows that a doubling of the flood probability will increase flood insurance premiums by more than 150 % of the current amount. For instance, the premiums corresponding to the four different future scenarios are, for the majority of the dyke-ring areas, substantially higher than the adjusted WTP amount. Under the RC40SLR24 and GE40SLR24 scenarios, there are, respectively, 30 and 32 dyke-ring areas with an RA insurance premium higher than €290, while these numbers increase to 42 and 46 for the respective scenarios with 60 cm SLR. However, this increase in premium can be kept significantly lower if the insurance is provided by an RN agency. The difference between the RA and the RN (re)insurance premium becomes larger with increasing flood risk. For instance, the RA (re)insurance premium for the current situation is approximately (2.5) 1.7 times its RN counterpart, which under the GE40SLR60 scenario increases to (4.2) 4.5 times of the related RN amounts. This implies that the participation of the governments or other RN agencies, either as a full insurer or as a reinsurer, in an insurance system for flood risk may make the system much more affordable and feasible.

## Main implications of the results for flood risk insurability

Climate change with a high SLR could result in very high (re)insurance premiums, and these premiums may reach the point where flood insurance becomes unaffordable for the majority of homeowners in the Netherlands. Moreover, private (re)insurance companies may lack sufficient financial capacity to cover extremely large flood losses and, therefore, may hesitate to offer flood insurance, especially when uncertainties about the insured amount are very high (Kunreuther et al. 2013).

An insurance scheme for catastrophe risk should not be seen only as a mechanism to share the burden of climate damage through the pooling of risks. It can also play an important role in providing incentives to homeowners to implement adaptive and risk-reducing measures. Given the expected climate change and socio-economic development in the future, a country like the Netherlands with a high flood risk exposure due to its low-lying land area can benefit from a PP insurance system that is accompanied by appropriate flood risk adaptation and mitigation measures. Participation of the government in a PP insurance system may have two main effects. First, it may enhance the feasibility and the affordability of an insurance arrangement because the government acts as a reinsurer of last resort by taking financial responsibility for the extreme losses. Second, a PP insurance system can provide an incentive to the government to implement long-term risk adaptation and mitigations measures, such as strengthening the dykes and making buildings less vulnerable to flood damage, which could substantially reduce future risk. For example, a study by Poussin et al. (2012) shows that damage mitigation measures, such as dry flood-proofing and wet flood-proofing buildings, could reduce flood risk in the Meuse Basin by between 21 and 40 %, while combining spatial zoning and mitigation measures could reduce potential damage by up to 60 % (Poussin et al. 2012). However, it has been shown that individuals often do not invest voluntarily in flood damage mitigation measures, because they underestimate their flood risk exposure and have a short investment horizon (Kunreuther 1996). Therefore, flood insurance could play an important role in stimulating people to implement adequate flood damage mitigation measures. For example, policyholders could be rewarded with some discount on the flood risk premium if they take measures that reduce flood risk through flood proofing their homes (Botzen et al. 2009). If premiums do not reflect risk, then development in flood-prone area may be encouraged, as has been argued to be the case with the National Flood Insurance Program in the USA (Kunreuther 1996).

However, flood insurance with fully risk-based premiums may be unaffordable in certain flood-prone areas, as is obvious from the large differences in (re)insurance premiums between the individual dyke-ring areas. Therefore, making flood insurance compulsory within a given dyke-ring area would serve to pool risks and spread the costs among households. Nevertheless, a certain degree of premium differentiation can be useful for providing incentives to homeowners to reduce flood risk by providing a price signal of risk, which can guide decisions to build in relatively safe areas and stimulate investments that reduce the vulnerability of properties to flooding (Paudel et al. 2012).

## Conclusions and recommendations

Based on four different scenarios—RC40SLR24, GE40SLR24, RC40SLR60, and RC40SLR60 which are two high and low socio-economic scenarios and two moderate and high climate change scenarios—this study provides probabilistic projections for flood damage and the corresponding (re)insurance premium estimates until the year 2040 for all 53 dyke-ring areas in the Netherlands. This paper is of practical relevance, as it provides many practical insights for the insured, the insurer, and the government, who are considering setting up flood insurance in the Netherlands.

Our results show that extreme climate change with a high SLR may lead to a substantial increase in potential flood risk and the corresponding (re)insurance premiums. In such a situation, a PP arrangement with a main focus on long-term structural adaptation and mitigation measures may offer a good solution for insuring flood risk in the Netherlands. On the basis of the results, we can draw four main lessons about whether a flood risk insurance system may be feasible and affordable under extreme climate change and socio-economic development in the future, and how such a system could be established in the Netherlands. First, extreme climate change with a high SLR seems to have a higher impact on flood damage and the corresponding (re)insurance premium compared with the either level of socio-economic development in the future. A SLR of 60 cm could lead to a potential (RN) flood insurance premium that is, on average, more than 17 times the current amount. In such a situation, flood risk insurance may be practically unfeasible. Second, (re)insuring large flood losses may become very expensive since extreme climate change and socio-economic development in the future may cause more frequent flood events with exceptionally high potential flood damage, due to much shorter return periods. For instance, the expected annual flood damage under the 60 cm SLR could increase significantly by 2040: namely from €58 million in 2015 to €2900 million. Under the lower-bound projection of 24 cm SLR, this amount could already increase to approximately €300 million. Third, a PP insurance system in which the government acts as a RN reinsurer of last resort, accompanied by comprehensive adaptation and risk reduction measures, could be a good solution for making flood risk insurance available in the Netherlands at an affordable price. As an illustration, the RN premiums under the current situation are about 2.5 times lower than their RA counterparts, while this could increase to about 4.9 times under the upper-bound scenario, namely GE40SLR60. This implies that the participation of the government in a PP insurance system could lower the premium by 4.9 times the RA amounts. Fourth, given the projected increase in flood risk, it is especially important that flood insurance contributes to climate change adaptation and provides the right incentives for flood risk reduction through prevention and the flood proofing of buildings. For that reason, a certain degree of premium differentiation can be helpful to provide incentives to homeowners to reduce flood risk by building in relatively safe areas and investing in risk reduction measures to protect their properties. The government could consider enforcing compulsory insurance for flood risk in order to spread the high insurance premiums of some of the dyke-ring areas across many policyholders and provide subsidies for low income homeowners.

Further in-depth research could further refine the analysis of the stochastic nature (frequency and severity) of flood damage. Damage and premium assessment methods should be subjected to comprehensive verification and validation processes to study the implications of climate change and socio-economic development. This research could be extended by integrating other climate change and socio-economic development projections than those used here. As comprehensive risk reduction measures are inevitable for keeping flood risk at acceptable levels and for the availability of flood insurance, an integration of a cost-benefit study of different flood risk adaptation strategies on the risk and premium estimations could be essential. Another aspect of a PP insurance scheme which could be studied is the willingness of insurers to participate in such a flood insurance system and the conditions they may place on the government concerning public investments in long-term risk mitigation and adaptation measures.

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