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Integrated Catastrophic Flood Model for Designing Robust Flood Insurance Program

Case study in Rijnmond-Drechtsteden area, the Netherlands

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Foreword

A significant part of the world population lives in flood-prone areas. Particularly, the Netherlands are vulnerable to a rising sea level and increasing frequency of river flooding. About 60 to 70 percent of the country's population and economic value is concentrated in areas that are at risk from flooding from the sea and/or rivers. The situation may be further worsen by climate change affecting in particular the see level rise and frequency and severity of weather-related catastrophic events.

The report describes the results of on-going joint IIASA-DELTARES[1] project on insurability of flood risks in outside dikes' areas in Rijnmond-Drechtsteden (RD) region around Rotterdam, the Netherlands. In the studies, the integrated catastrophic risks management model of ESM (ICRM, www.iiasa.ac.at/researchPrograms/ESM/) combines a HIS-SSM model (Highwater Information System – Damage and Casualties Module) and stochastic quantile-based optimization procedures to generate scenarios of flood losses and quantify robust insurance policies for flood-prone locations outside main flood defense system, i.e. outside dike rings.

The project develops approaches for designing robust "public-private" flood-loss sharing programs comprised, e.g., of private flood insurance, central and local governments, and financial instruments (contingent credits, cat bonds, etc.) for "buffering" the risks. Involvement of governments and introduction of financial instruments increases the demand for the insurance and helps fulfill its liabilities avoiding insolvency.

The project enables exchange of practical and methodological experience between IIASA and DELTARES: IIASA develops novel methodologies and practical approaches for integrated catastrophic risks management, discounting, security and robust solutions (Systemic Risks, Security and Robust Solutions project, ASA), applied

[1] Deltares (http://www.deltares.nl/en) is an independent institute for applied research with a unique combination of knowledge and experience in the field of water, subsurface and infrastructure. Deltares is frontrunner in the development and application of knowledge to meet the short- and long-term challenges in the physical planning and management of vulnerable deltas, coastal areas and river basins. The majority of its projects are interdisciplinary to address the multiple interests in management of water resources. Deltares plays a central role in the Dutch national climate adaptation programme – the Deltaprogramme – both in direct policy supportive research and associated scientific research programmes (e.g. Knowledge for Climate, Building with Nature, Flood Control)

in case studies of catastrophic floods, wind storms, earthquakes, outbreaks of livestock related diseases, etc. DELTARES is involved in practical water management projects such as flood protection (Project for the development of a new test instrumentarium based on flood risk assessment); environment, e.g. water pollution treatment, taxation; etc. Joint research proposes new robust conclusions for policy makers.

Abstract

As flood risks grow worldwide, a well-designed insurance engaging various stakeholders becomes a vital instrument in flood risk management. This paper focuses on the design of a multi-pillar flood-loss sharing program involving partial compensation to flood victims by the central government, the pooling of risks through a private insurance on the basis of location-specific exposures, and a contingent ex-ante credit to reinsure the liabilities. The analysis is guided by an integrated catastrophe risk management (ICRM) model consisting of GIS-based flood model and a stochastic optimization procedure with respect to location-specific risk exposures. To achieve the stability and robustness of the program towards floods with various recurrences, the ICRM uses stochastic optimization procedure, which relies on insolvency constraint and Conditional Value-at-Risk (CVaR) indicators. Two alternative ways of calculating insurance premiums are compared: the robust derived with the ICRM and the traditional average annual loss approaches. The applicability of the ICRM model is illustrated on a case-study of a larger Rotterdam area outside main flood protection system in the Netherlands. Our numerical experiments demonstrate essential advantages of the robust premiums, namely that they: (1) guarantee program's solvency under all (or a percentile) flood scenarios rather than one average event; (2) establish a tradeoff between the security of the program and the welfare of locations; (3) decrease the need for other risk transfer and risk reduction measures.

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Integrated Catastrophic Flood Model for Designing Robust Flood Insurance Program:

Case Study in Rijnmond Drechtsteden area, the Netherlands

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1 Introduction

A significant part of the world population lives in flood-prone coastal and delta areas. About 23 percent of the world population residing coastal zone and 10 percent of the population living in low-lying areas [39] are threatened by floods. For example, damages from coastal storms and floods in the USA in 2012 accounted for almost $54 billion of estimated overall losses [40].

Particularly, the Netherlands are vulnerable to a rising sea level and an increasing frequency of river flooding. About 60 to 70 percent of the country's population and economic value is concentrated in areas that are at risk from flooding from the sea and/or rivers. The situation may be further threatened by climate change affecting in particular the see level rise. Coastal and delta areas were historically developed due to their proximity to marine and river transportation. Further developments are attracted to historic centers by agglomeration forces as well as by rich environmental amenities. As a result exposure and vulnerability in coastal areas rapidly increase due to the clustering of population and growth of property values in flood-prone areas [26]. As a matter of fact, urban developments are capital intensive and are highly path-dependent [9], which means that where and how much of coastal and riverfront properties get developed depends on the series of previous decisions, e.g. location of past developments and past flood risk management (FRM) policy. A significant time lag between FRM decision and actual risk reduction demands a long-term vision and a comprehensive approach accounting for feedbacks and externalities [14], [22].

Worldwide governments develop FRM policies that aim to reduce flood risk. It can be reduced by decreasing either probabilities of the hazard, i.e. through structural engineering solutions such as dikes or beach nourishments, or the damages, i.e. through zoning, financial measures to distribute risk across stakeholders, or flood-proofing buildings. Flood safety is often assured by structural flood defense measures, spatial planning, subsidized flood insurance or disaster relief programs. These measures are mostly funded by governments, i.e. society as a whole independently of the benefits the individuals in particular locations receive from a certain FRM measure. This unintentionally impedes any incentives for local stakeholders (households, business, local jurisdictions) to take measures to make flood-resilient choices reducing overall flood damage at macro-level [6], [33], [46]. In the USA, public investments in infrastructure and levees in coastal areas led to rapid population growth and consequent growth of flood risk [4].

In the Netherlands, the Delta works and flood defenses provided the highest safety standards in the world while, simultaneously, the population and economic activities in hazard zones increased at a speed never observed before [26]. It is recognized that governments should engage stakeholders to assure effective FRM policy [13], which avoids mounting costs for, firstly, subsidizing developments in flood-prone areas, and then compensating damages. Thus, there need to be economic stimuli to encourage individuals in making flood-resilient choices and incorporate long-term societal needs, such as curbing flood risks, into short-term oriented local decisions today.

Flood insurance is considered a vital element of FRM policy [38]. A well-designed flood insurance program: (i) spreads the risk across actors, locations and time and assures funds available for loss compensation [35], (ii) increases public awareness of flood risks [36], (iii) often leads to price discounts which reflect capitalized risks [7], (iv) promotes damage mitigation measures [8], and (v) improves land use efficiency [43]. Such a public-private partnership (PPP) may assume, for example, a financial layer of contributions from property owners (households and businesses), a layer of private insurance, a risk transfer layer through reinsurance or/and catastrophe bonds, and finally a layer of government contribution in a form of a cap or reinsurances of extreme losses. This collective effort involving multiple stakeholders requires the analysis of their mutually dependent risk exposures. For example, if an insurer wants to decrease the chances of bankruptcy which may happen if he faces a loss greater than a certain level, he may decrease the chances by imposing higher premiums or decreasing coverage, take reinsurance or buy a catastrophe bond. The burden of losses is shifted away from the insurer but may be unevenly redistributed among other stakeholders, i.e., individuals, government, reinsurance companies, and lead to their instability or ruin. Thus, the success of a loss-sharing program depends on the mutual stability of the involved heterogeneous stakeholders. This requires the analysis of complex multivariate joint probability distributions of losses dependent on the frequency and intensity of hazards leading to the development of region-specific catastrophe flood models. Traditional catastrophe models comprise several modules: a hazard generator, vulnerability and financial modules. Catastrophe models of today are very comprehensive. Open source and proprietary catastrophe models (e.g. developed by

AIR, RMS, EQECAT) use rich spatial data and estimate premiums based not only on historically observed risks but also considering various socio-economic and climatic scenarios [1], [23], [25]. However, in many of these models the pricing of catastrophe risk is based on the Average Annual Loss (AAL) without explicit accounting for goals and constraints of the involved stakeholders. A risk load is often expressed in terms of standard deviation) and administrative costs load [34], or only on AAL [1]. Due to the skewedness of catastrophe risks as well as spatio-temporal dependencies of losses on past and current policies, this approach may appear misleading [2], [5].

In contrast, the quantile-based, in particular, Value-at-Risk (VaR, [42], [47]) indicators, gain popularity for determining catastrophic insurance policies [2], [41]. Geographically-detailed catastrophe models combined with quantile-based risk indicators and stochastic optimization procedures allow proper capturing of spatio-temporal profiles of catastrophe risks and avoiding irreversible shocks to insurance arrangements and involved stakeholders [17], [18].

In this paper, we focus on a quantile-based approach to estimate location specific risk-based premiums outside dikes in the Rijnmond-Drechtsteden (RD) area around Rotterdam, the Netherlands. We apply an integrated catastrophe risk management (ICRM[2]) model combining a HIS-SSM model (Highwater Information System – Damage and Casualties Module, [31]) and a stochastic optimization procedure to generate scenarios of flood losses and quantify robust insurance policies for flood-prone locations outside main flood defense system, i.e. outside dike rings. Until recently insurance from river and coastal flooding did not exist in the Netherlands, leaving post-disaster relief program as the only financial instrument in FRM. The issue has been debatable since some consider it unfeasible [30, 32] while others think it is feasible under various reinsurance schemes [1]. Yet, the first flood insurance contracts became available at the end of 2012 [3] but only for areas protected by dikes. Although several studies exist on how to enhance flood insurance system in the Netherlands [1], [27], [28], [30], [32], they primarily analyze inside-dikes flood risks. For example, Aerts and Botzen [1] apply AAL principle to derive flood-related insurance premiums for large dike-ring areas in the Netherlands.

This paper studies the insurability of the flood risk in RD region from the view point of insurance supply and demand. The balance between supply and demand substantially depends on the choice of coverage and premiums: the choice of insurance coverage and premiums reflects the capacity of insurance to sustain the floods and the wiliness of

[2] Integrated Catastrophic Risk Management model (ICRM) has been developed at International Institute for Applied Systems Analysis (IIASA). For the description see e.g. Ermolieva, T., Ermoliev, Y., Norkin, V. 1997; Ermolieva, T., Ermoliev, Y. 2012; Amendola, A., Ermolieva, et al. 2012 and further references therein.

individuals to pay the premiums. We use such economically sound risk indicators as expected overpayments by “individuals” and expected shortfall of the insurance to derive robust “fair” premiums and coverage to achieve the desirable probability of insurance default and balance the supply and demand. In the RD region, the ICRM is used for the design of a robust flood loss sharing program based on pooling risks through location-specific flood insurance, partial compensation to the flood victims by the central government, and a contingent credits to the insurance for “buffering” the risk. Involvement of the government and introduction of the contingent credit increases the demand for the insurance and helps fulfill its liabilities avoiding insolvency.

The structure of the paper is as follows. Section 2.1 presents a stylized model of insurance business illustrating the shortcomings of the AAL approach to risk pricing and the need for the insolvency (quantile-based) constrains and the stochastic optimization for robust management of catastrophe risks. Section 2.2 outlines the methodology of the ICRM model extending the basic model of Section 2.1 to a multi-agent spatially explicit and dynamic stochastic optimization model involving analytically-intractable multivariate joint loss distributions of the agents. Section 3 describes the case study of a larger Rotterdam area and available modules and data. Section 4 reports the results of numerical experiments in terms of spatial distribution of insurance premiums and dynamics of the insurance fund reserves. It identifies the differences between the model-derived robust insurance premiums and coverage in comparison to actuarial approaches based on AAL. Conclusions are summarized in Section 5.

2 Integrated Catastrophe Management Model

2.1 A Stylized Model of Insurance Business

In the Netherlands, flood safety standards in the protected areas vary between 200 to and 10,000 -year floods return periods [29]. In the areas outside the main protection system flood return periods may occur starting from once every 10 years. Although floods may happen rarely, their abrupt occurrence in time and space comes as “spikes” that cannot be properly modeled on “average”. For example in Dordrecht, a flood with a return period of 2000 years causes damage of 1.5 billion euro. According to the AAL approach an expected damage is 750,000 euro per year including damage to private (households and businesses) and governmental actors. This is a reasonable affordable amount except that this damage is not going to occur in small annual portions – all 1.5 billion will come at once. Thus, annualization of expected damages and estimation of insurance premiums based on that average may be misleading and could undermine the financial stability of an insurance program and overall risk management policy. Treatment of catastrophic damages requires quantile-based stochastic optimization approaches. In what follows we illustrate this with a simple model that addresses the "abruptness" feature of catastrophes. In Section 2.2 this model is generalized to a framework involving goals and constraints of multiple agents and in Section 3.2.5 presents numerical experiments to test the model using data from the RD case study region.

Consider a simple stylized model of insurance business (see, e.g [10], [24]). Financial stability of the insurer is characterized by the dynamics of his risk reserve accumulation, i.e., the capital he has at the disposal to pay out claims. In the simplest case the risk reserve r^t at time t is defined as $r^t = r_0 + \pi^t - A^t$, $t \geq 0$, where π^t and A^t are aggregated premiums and claims correspondingly, and r_0 is the initial risk reserve. The process $A^t = \sum_{k=1}^{N(t)} S_k$, where $N(t)$, $t \geq 0$ denotes a random number of claims in interval $[0,t]$ (e.g., a Poisson process) with $N(0) = 0$, and $\{S_k\}_1^\infty$ is a sequence of independent and identically distributed random variables (claims) — in other words, replicates of a random variable S. In this model, the inflow of premiums π^t pushes r^t up, whereas the random outflow A^t pushes r^t down (Figure 1).

The main problem of the insurer is to avoid the situation when r^t drops below the "vital" level (ruin) — in our example, equal to 0. In insurance industry, the bankruptcy is allowed only with a certain insolvency probability $\Psi = P\{r^t \leq 0 \text{ for some } t,\ t > 0\}$ (once in 1000 years, $\Psi = 1/1000$).

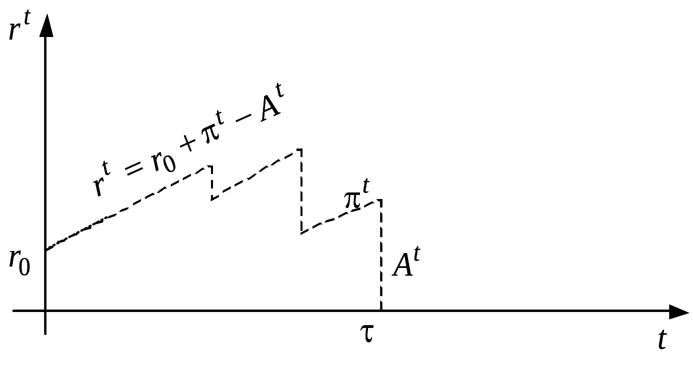


Figure 1: Trajectory (scenario) of the risk reserve r^t subject to the random process of claims.

The stability of an insurer may be improved in many ways, e.g., by adjusting premiums. The deterministic or AAL approach to calculation of premiums is very simplified, as illustrated by the following calculations. Assume that $N(t)$, S_k, are independent, $N(t)$ has intensity σ, i.e., $E\{N(t)\} = \sigma t$, and $\pi^t = \pi t$. Then the expected profit over the interval $[0,t]$ is calculated as a difference between the expected annual premiums and claims, i.e. $(\pi - E(S)\sigma)t$. The expected profit increases in time if $\pi - E(S)\sigma > 0$. This model ignores complex interdependencies among the timing of claims (temporal clustering), their sizes, and the subsequent possibility of ruin, $r^t \leq 0$. In this formulation, complex random process r^t is replaced by a simplified linear one in t function, $r^t = r_0 + (\pi - \sigma ES)t$. The difference $\pi - \sigma ES$ is the "safety loading". It follows from the strong law of large numbers that $[\pi^t - A^t]/t \to [\pi - \sigma ES]$ with the probability of 1. Therefore, in the case of positive safety loading, $\pi > \sigma ES$, we have to expect random profit $\pi^t - A^t$ for a sufficiently large t would also be positive under the appropriate choice of premium $\pi = (1+\rho)\sigma ES$, where ρ is the "relative safety" loading $\rho = (\pi - \sigma ES)/\sigma ES$. However, this holds only if ruin does not occur before time t. As illustrated in Figure 2, despite that the growth of risk reserves r^t is guaranteed on average, the ruin of the real growth process r^t may occur. In other words, the substitution of the complex jumping process r^t by a simple deterministic model forecasting gradual growth of the reserve may lead to unforeseen collapses. Only a stochastic model is able to estimate the demand for such financial risk management measures as risk-based flood insurance, borrowing, contingent credits, or governmental bonds. It is also possible to reduce the severity of the distribution of claims by various loss reduction mitigation measures. However, all this is possible only by analyzing the probability of ruin Ψ. The claim size S depends on the coverage of the insurer operating on geographically distinct locations. In general, various decision variables affect Ψ. Important decision variables are r_0, π, and reinsurance arrangements. The reduction of Ψ to acceptable levels can be viewed as the so-called chance constraint stochastic optimization problem (see [16]). The complexity is associated with the random jumping process A^t (claims), with analytically intractable dependencies of A^t on decision variables, which requires specific *quantile-based stochastic optimization methods*. Stochastic optimization produces decisions, which fulfill the constraint Ψ with guaranteed probability, i.e., the *decisions are robust* with respect to desired proportion (percentile) of all flood events. Throughout the paper we use the term "robust" to define such an insurance program that: 1) fulfills goals and constraints of the involved stakeholders; 2) remains solvent under all (or a percentile) flood scenarios rather than one (average) event.

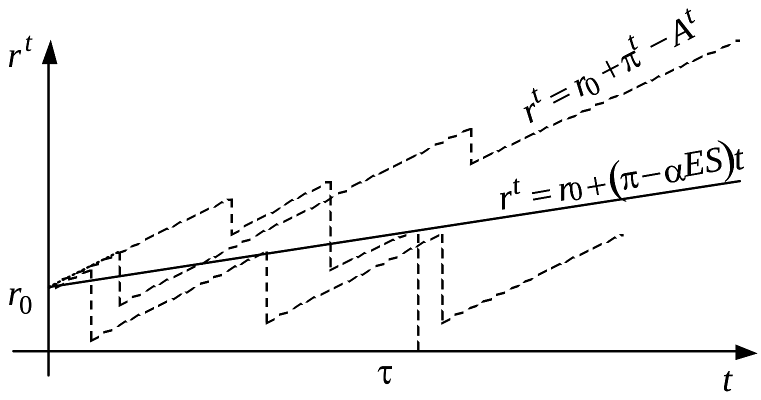


Figure 2: Expected and real growth of the risk reserve. There is an exit scenario due to an extreme event at time τ, which depletes the safety loading.

2.2 Stochastic Integrated Catastrophe Risk Management Model

Previous section briefly outlined some methodological complexities related to catastrophe management. Now we introduce a general integrated catastrophe risk management model (ICRM) developed at IIASA [17], [19], [21]. To account for multiple risk management stakeholders, the insurance model of section 2.1 is modified as follows. The study region is subdivided into sub-regions or locations $j = 1,2,...,m$. Locations may correspond to a collection of households, flood-protection zone, municipality, etc. For example in [1] the locations correspond to dike-protected areas. We assume that for each location j an estimation W_j of the property value or "wealth" of this location exists, which includes values of houses, lands, factories, etc.

Suppose that n agents, $i = 1,...,n$, (insurers, governments, re-insurers) are involved in the loss sharing program. They may have contracts with locations to cover their losses. Each agent i has an initial fund or a risk reserve R_i^0 (similar to the model in section 2) that in general depends on magnitudes of catastrophic events, as it is illustrated with numerical experiments in Section 3. Assume that the planning horizon covers $t = 0,1...,T-1$ time intervals. The risk reserve R_i^t at each t is calculated according to the following formula:

$$R_i^{t+1} = R_i^t + \sum_{j=1}^{m}\left[\pi_{ij}^t(q^t) - c_{ij}^t(q^t)\right] - \sum_{j \in \mathcal{E}_t(\omega_t)} L_j^t(\omega_t) q_{ij}^t \,, \qquad (1)$$

where $i = 1,2,...,n$, $q^t = \left\{q_{ij}^t,\ i = \overline{1,n},\ j = \overline{1,m}\right\}$, q_{ij}^t is the coverage of a company i in location j at time t, $\sum_{i=1}^{n} q_{ij}^t \le 1$, $\pi_{ij}^t(q^t)$ is the premium from contracts characterized by coverage $\left\{q_{ij}^t\right\}$ (full coverage of losses corresponds to $q_{ij}^t = 1$), and $c_{ij}^t(q^t)$ are transaction costs or administrative, running or other costs. $L_j^t(\omega_t)$ is the loss (damage) in location j caused by a catastrophe ω_t at time t. Random catastrophic events $\omega = (\omega_0, ..., \omega_{T-1})$ may affect a random number of different locations. In general, a catastrophic event at time t is modeled by a random subset $\varepsilon_t(\omega)$ of locations j and its magnitude in each j. The losses $L_j^t(\omega_t)$ depend on the event ω_t, mitigation measures (e.g., dikes against flooding), and vulnerability of property values in j.

Variables q_{ij}^t and $\pi_{ij}^t(q^t)$ allow the characterization of the differences in risks at different locations. It is assumed that all agents may cover different fractions of catastrophic losses from the same location. Variables q_{ij}^t interconnect the processes of R_i^t, $i = 1,2,...,n$ (e.g., $\pi_{ij}^t(q^t)$, $c_{ij}^t(q^t)$, $L_j^t q_{ij}^t$) with each other. Inflows of premiums push trajectories of R_i^t up, whereas claims and transactions costs push them down.

In the case of a catastrophe, a location j faces losses (damages) L_j^t. Individuals at this location receive compensation $L_j^t q_{ij}^t$ from company i when such a loss occurs, and pay insurance premiums $\pi_{ij}^t(q^t)$. If W_j^0 is the initial wealth (property value), then the location's j wealth at time $t+1$ equals:

$$W_j^{t+1} = W_j^t + \sum_{i=1}^{n} (L_j^t q_{ij}^t - \pi_{ij}^t(q^t)) - L_j^t, \; t = 0,1,.... \tag{2}$$

Equations (1) and (2) represent rather general processes of accumulation. Let us denote the decision variable by a vector x, which includes components of coverage q and feasible mitigation measures. For each insurer (agent) i consider a stopping time τ_i for process $R_i^t(x,\omega)$, i.e., a random variable with integer values $t = \overline{0,T}$. The event $\{\omega : \tau_i = t\}$ with fixed t corresponds to the decision to stop process $W_i^t(x,\omega)$ after time t. Examples of τ_i may be the time of the ruin before a given time T: $\tau_i(x,\omega) = \min\{T, \min[t : R_i^t(x,\omega) < 0, t > 0]\}$ (in which case τ_i is a rather complex implicit function of x) or the time of the first catastrophe, $t = \tau$.

Assume that each agent, i, and location, j, maximize their "wealth" at $t = \tau$, i.e., they are concerned with the resilience against possible catastrophes. In general, the notion of wealth at t requires an exact definition, as it must represent in a sense the whole probability distribution of R_i^τ, W_i^τ. The performance of insurance depends on whether the accumulated fund $\sum_{t=1}^{\tau}\left[\sum_{j=1}^{m}\left[\pi_{ij}^t(q^t) - c_{ij}^t(q^t)\right]\right]$ is able to cover claims $\sum_{j \in \mathcal{E}_\tau(\omega_\tau)} L_j^\tau(\omega_\tau) q_{ij}^\tau$.

Thus, insurers will maximize their wealth, which depends on the (random) balance of income and payments:

$$\vartheta_i^\tau = \sum_{t=1}^{\tau}\left[\sum_{j=1}^{m}\left[\pi_{ij}^t(q^t) - c_{ij}^t(q^t)\right]\right] - \sum_{j\in\mathcal{E}_\tau(\omega_\tau)} L_j^\tau(\omega_\tau)q_{ij}^\tau .$$

The stability of an insurer is determined by the probability of the event

$$E_1 = \{\vartheta_i^\tau < 0\}. \quad (3)$$

Individuals (locations) maximize their wealth, which depends on whether the amount of premiums that they pay to the insurer does not exceed the compensation of losses at time $t = \tau$:

$$v_j^\tau = \sum_{t=0}^{\tau} \pi_{ij}^\tau(q^k) - L_j^\tau(\omega_\tau)q_{ij}^\tau .$$

Therefore, the "financial" stability of locations depends on the probability of the event

$$E_2 = \{v_i^\tau < 0\}. \quad (4)$$

Inequalities (3)–(4) define important events, constraining the choice of decision variables, e.g., insurance premiums, coverage. The probability of events (3)–(4), i.e., underpayments to insurers and overpayments by individuals, determine the stability (resilience) of the scheme. This can be expressed in terms of the probabilistic constraint

$$P[E_1, E_2] \le p , \quad (5)$$

where p is a desirable probability threshold of the program's failure (default) that occurs, say, only once in 100 years. Constraint (5) is similar to an insolvency constraint, a standard for regulations of the insurance business. In stochastic optimization [16], it is known as the so-called chance constraint. Note, however, that this constraint does not account for the attained values of E_1 and E_2. The main goal in setting up the insurance scheme can now be formulated as the minimization of expected total losses

$$F(x) = E\sum_{ij}(1 - q_{ij})L_j^\tau$$

including uncovered (uninsured) losses by the insurance scheme subject to chance constraint (5), where vector x, in the most simple example, consists of the components π_{ij} and q_{ij}. There are important connections between the minimization of $F(x)$ subject to highly non-linear and possibly discontinuous chance constraints (5) and the minimization of convex functions, which have important economic interpretations.

Consider the following function:

$$G(x) = F(x) + \alpha \sum_i E \max\{0, \vartheta_i^\tau\} + \beta \sum_j E \max\{0, \nu_j^\tau\} \qquad (6)$$

where α, β are positive parameters. It is possible to prove (see general results in [20] that for large enough α, β the minimization of function $G(x)$ generates solutions x with $F(x)$ approaching the minimum of $F(x)$ subject to (5) for any given level p.

The minimization of $G(x)$, as defined by (6), has a simple economic interpretation. Function $F(x)$ comprises expected direct losses associated with the insurance program. The second term quantifies the expected shortfall of the program to fulfill its obligations; it can be viewed as the expected amount of ex-post borrowing with a fee α needed for this purpose. Similarly, the third term can be interpreted as the expected ex-post borrowing with a fee β needed to compensate overpayments. Obviously, large enough fees α, β will tend to preclude the violation of (3)–(4). Thus, ex-post borrowing with large enough fees allows for a control of the insolvency constraints (5). Functions (6) is nonsmooth due to the presence of max operations. In (6), nonsmooth risk functions are used to guarantee a trade-off between profits and risks of underestimating losses and overestimating profits with substitution coefficients α and β [3].

In the following section we adjust the model for the analysis of an insurance program for the areas outside the main protections system close to Rotterdam. The ICRM is used for the design of a robust flood loss sharing program based on pooling risks through location-specific flood insurance, partial compensation to the flood victims by the central government, and a contingent credit to the insurance for “buffering” the risk.

3 Case Study and the Revised Model

3.1 Case study region

The case-study covers the area outside dike rings in the RD region including Rotterdam (Figure 3.a). Though many studies exist on how to enhance flood insurance system [1], [27], [28], [30], [32] in the Netherlands, they analyze primarily inside-dikes flood risks and consequent insurance premiums. This paper focuses on flood risks in the areas outside the main protections system and quantifies an example of a robust flood-loss sharing insurance program.

The RD region is prone to both river and coastal flooding. The areas outside dike rings (Figure 3.b) differ from the areas inside the main protections system in terms of

[3] Minimization of total expected losses under explicit “insolvency” constraints leads to a general nonsmooth stochastic optimization problem.

physical aspects of flood risk and responsibilities among stakeholders in a number of ways (Table 1). Most important is that currently flood protection within the dike rings is fully in the responsibility of the government, while for the outside dike ring areas there are no safety standards guaranteed by the government. New investments are at the risk of individuals, with no governmental compensation provided in the case of a hazard event. The Netherlands did not have insurance from river or coastal flooding until recently, what makes it difficult especially for the areas outside the main protections system to: (i) communicate risks, (ii) to take individual action to distribute losses in time, and (iii) to create stimuli for damage mitigation actions such as additional flood-proofing of houses.

Table 1: Physical aspects of flood risks and responsibilities among stakeholders in the areas outside dike rings in comparison with the protected ones.

Areas outside the main protections system	Protected areas within a dike-ring
Flood and damage characteristics	
Government does not guarantee any safety standards. Actual return periods vary between 1:5, 1:10 years to 1:100, 1:1000 years or less frequent (e.g. 1:10000 for new harbor areas)	Safety standards assigned by law: 1:200 to 1:1250 years – river floods 1:2000 and 1/4000 for the estuary (tidal rivers) 1:4000- to 1-10.000 years – coastal floods.
Probability of flood is location-specific and may be much higher than the official safety standard in the neighboring protected areas.	One homogeneous safety standard for the whole dike-ring.
Properties are elevated above sea level, i.e. on dunes, man-made high elevation grounds, etc.	Many developments inside dike rings are below sea level (up to -6 meters).
Flood water comes with low velocity and goes away quickly.	Flood water comes with high velocity and stays for a prolong period.
Flood protection and roles of different parties	
Developments are at the risk on individuals (households or firms). Municipalities may prohibit some socially-vital activities in these areas, e.g. hospitals.	Government is responsible to assure safety standards prescribed by law.
Individuals are responsible for their own protection and damage in the case of flooding.	Government refund any possible damage from a flood event.
Flood insurance does not exist but is argued to be financially feasible [44].	Until recently flood insurance did not exist. First contracts to insure flood risks became available in 2013 [3]. The issue is debatable since some consider it unfeasible [30], [32] while others think it is feasible under various reinsurance schemes [1].

Figure 3.a: Case-study region (this paper considers only the areas outside the primary embankments, see Figure 3b).

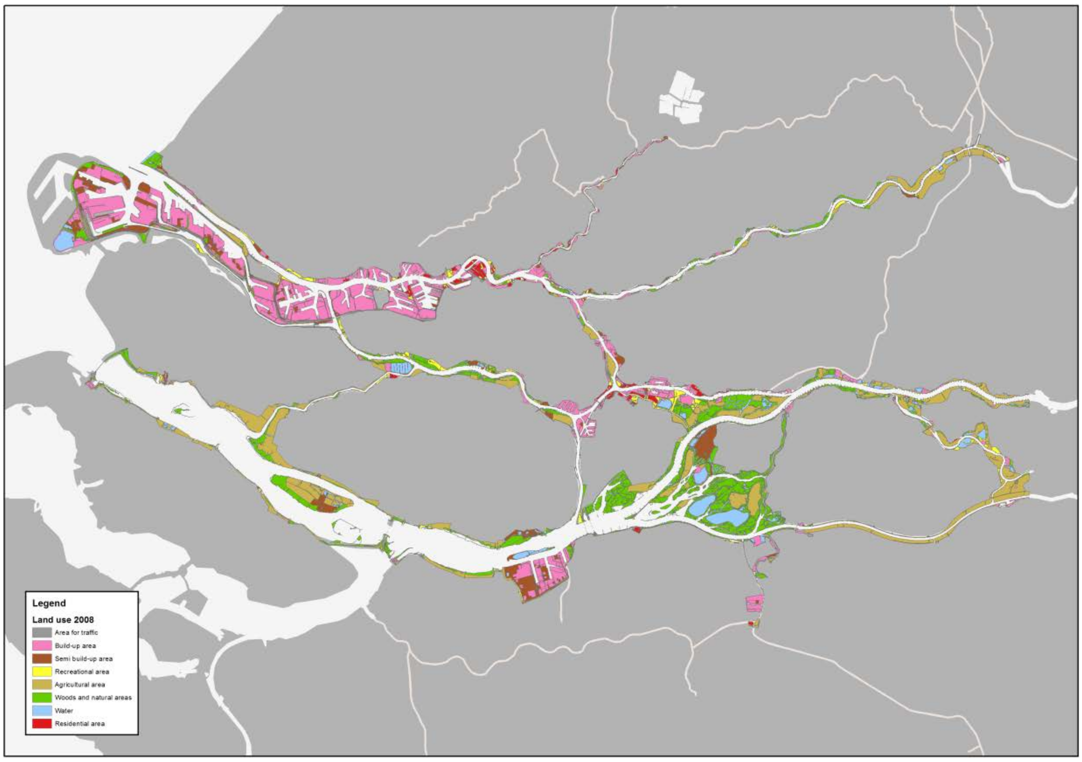


Figure 3.b: Land use in the Rijnmond-Drecthsteden region (the colored area is the area outside the main protection system). Source: [11].

3.2 Modules and data

An integrated catastrophe management model capable of quantifying optimal location-specific insurance premiums and coverage comprises several vital components. The hazard, exposure and vulnerability modules (I, II and III in Figure 4) provide data inputs to estimate potential losses, i.e. damages in each location (Figure 4, IV). Based on the estimated damages, the ICRM model runs stochastic optimization under a range of constrains across stakeholders (insurance companies, households and firms, government ts, etc) to produce optimal risk-based location-specific insurance premiums and coverage (Figure 4, V.).

We describe each module separately when discussing the data inputs into the ICRM model.

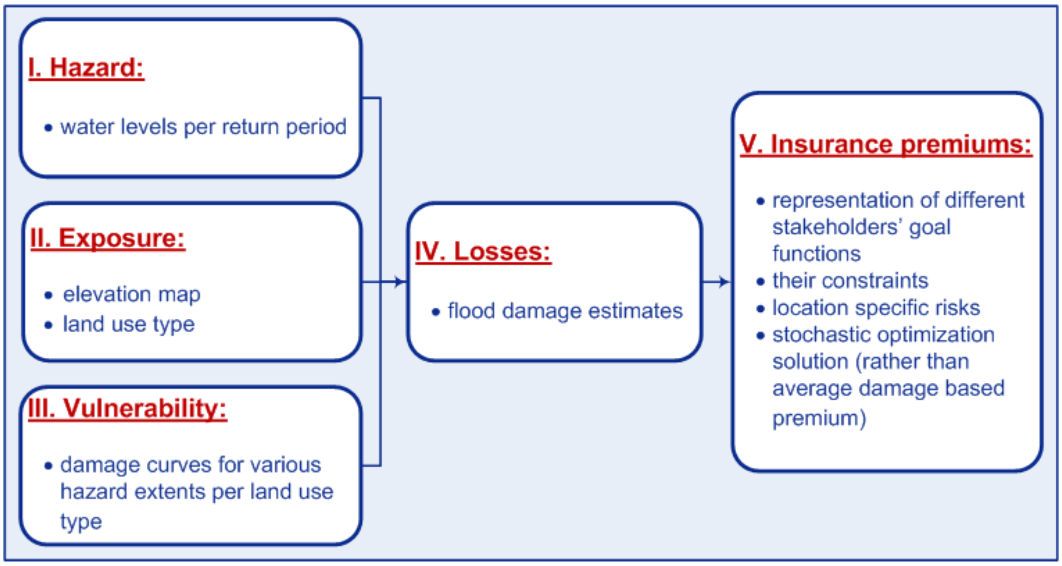


Figure 4: Scheme of modules and data flows.

3.2.1 Hazard module (I)

The geo-referenced estimates of water depth in the areas outside the main protection systems in RD for various return periods floods were estimated using water level calculations and flood mapping techniques. The basis elevation data is 5mx5m cell size LIDAR data was corrected to include local small embankments and structures [11]. The resulting 5m water depths are used in the Deltaprogramme[4] and were reviewed by the

[4] Dutch climate adaptation program, http://www.deltacommissaris.nl/english/topics/

Rotterdam Harbour Authority. In this paper we consider spatio-temporal damage patterns for “current climate” scenario and three flood scenarios, i.e., 10-, 100-, and 1000- year floods.

3.2.2 Exposure data (II)

Exposure data (II) includes geographically explicit information on different land-uses in the case study region, including various geographically referenced data concerning, e.g., economy, transportation networks, buildings, population. For the case study region, these data have been compiled from HIS-SSM model (Highwater Information System – Damage and Casualties Module, [31]). The HIS-SSM is often used to support policy decisions reading flood risk management for inside-dike areas in the Netherlands. Exposure data include assumptions about economic growth and infrastructure expansion in the case study region. The data on land use, roads, railroads and houses has been updated compared to earlier HIS-SSM versions [31]. The new data on houses provides detailed information on the location of each individual building and its attributes (number of houses, elevation etc.) [11].

3.2.3 Vulnerability module (III)

Vulnerability curves reflecting damage for a particular land use at a particular water level and flood wave speed are the part of HIS-SSM model. Originally designed for the inside-dikes areas which are relatively homogeneous with respect to elevation, HIS-SSM model operates at the scale of 100m ×100m. Since properties in the outside dikes areas are often elevated on an individual basis and vary greatly across locations, water-levels, and consequently damage, are highly location-specific. To be applicable to model damages in the outside-dikes areas the resolution of the HIS-SSM calculations has been reduced from 100m to 5m cell to get all the obstructions, small levees and local height represented well in the water depth and vulnerability maps.

3.2.4 Loss estimates (IV)

Location specific damages (losses) for each of the 10-, 100-, 1000- year floods were estimated by HIS-SSM combining the data from the “Hazard”, “Exposure”, and “Vulnerability” modules. The damage estimation in HIS-SSM model was adjusted to account for the specifics of the outside-dikes areas. Specifically, the damage functions and categories for residential buildings have been improved, categories and damage figures of agriculture, natural areas and the data on the presence of houses has been taken from another more detailed source and damage functions have been adapted. To capture the situation in the areas outside main protection system damage figures to agricultural and natural areas and construction sites have also been adapted. The damage to agricultural and natural areas have been set to zero. This was done since the high values for those categories are based on the presence of machinery, stables and high yield varieties, which is realistic only in areas with very low flood probabilities.

The agricultural areas outside the primary defenses are situated along the rivers and are used for cattle breeding in summer. Cattle is removed in winter when peak flows occur, what makes damage negligible. The large natural areas outside the primary defenses become deeply flooded twice a day (every high tide) and their ecosystems benefit from the floods.

These improvements in loss estimation resulted in a 60 percent reduction of damages compared to the damages estimated in 2011 [11]. In 2013 further improvements will be carried out mainly on damage figures, functions and data for companies and industries. Yet, these figures should be considered with care as several adjustments, especially to 1:10 years damage estimations, are likely to come in the next few years. Damage figures used in the current paper should be treated as illustrative to show the applicability of the ICRM model and its potential practical use.

Table 2: Losses from floods in the RD area

	Damage, in 2012 euro			Expected damage across 3 flood scenarios	
	Flood 1:10	Flood 1:100	Flood 1:1000	in 2012 euro	in %
Infrastructure	45,195,972	62,531,184	96,080,670	5,117,549	35
Households	20,248,656	54,404,334	96,487,015	2,577,560	18
Businesses	51,452,184	154,445,118	309,459,919	6,752,502	47
Total damage (direct and indirect)	**116,896,812**	**271,380,636**	**502,027,604**	**14,447,611**	**100**
Number of affected citizens	**1,804**	**7,354**	**11,585**	---	---

Damage for the areas outside main protection system were calculated for the three return periods: 10-, 100- and 1000-year floods (Table 2). These figures are current best estimates for all damage categories across include both direct and indirect damage across 27 land use types. Thus, the figures are much higher than for example in [44], which estimated damage to houses and house content only. The annual damage per residential house excluding any damage to firms and infrastructure in the areas outside the main protections system varies from 4-5 euro in Rotterdam and Dordrecht up to 225-613 euro in Bergambacht and Nederlek for the current climate [44].

Figures 5 and 6 display patterns of selected flood damages in outside-dikes areas generated by adjusted HIS-SSM for the current climate.

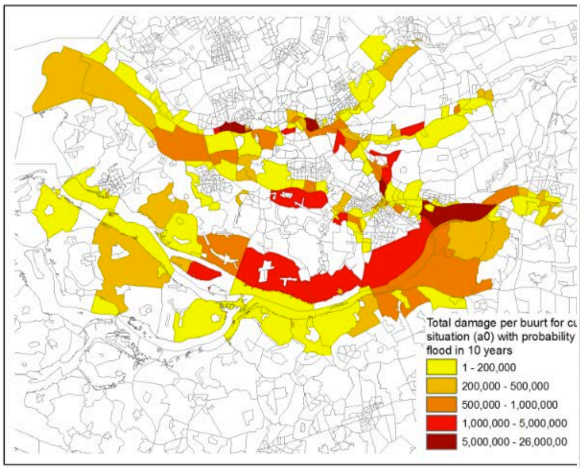


Figure 5: Losses, 10-yr. flood

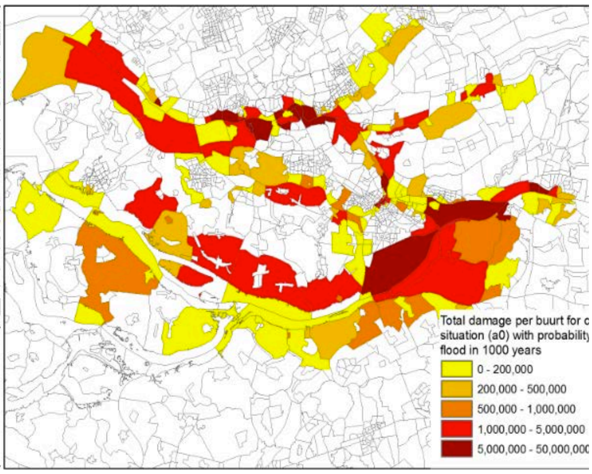


Figure 6: Losses, 1000-yr. flood

3.2.5 Modified Stochastic Integrated Catastrophic Risk Management Model (ICRM, V.)

In numerical experiments, the general model (1)–(6) of Section 2 is adjusted to capture the spatial resolution and patters of the flood scenarios in the RD region. From the model, it is possible to conclude about the optimal FRM insurance policies including the composition of insurance arrangement, level of initial fund reserve, the required governmental insurance coverage, the demand for other financial instruments (contingent credits, cat. bonds, etc.), as it is discussed in numerical experiments.

We assume that only one "aggregate" insurer or a catastrophe fund operates in the region. Similar to Section 2, the main goal of the insurer is to minimize expected uncovered losses:

$$E\sum_j (1-q_j)L_j(\omega)\,. \tag{7}$$

The model-derived robust premiums fulfill fairness constraints on non-overpayments by individuals and stability of the insurance:

$$P\{\pi_j - q_j L_j(\omega) > 0\} < \gamma \text{, for all locations } j = \overline{1:N}\,, \tag{8}$$

$$P\{\sum_j (\pi_j - q_j L_j(\omega)) < 0\} < \phi\,. \tag{9}$$

where q_j is insurance coverage to locations (households) j, π_j is the level of premiums paid by locations/households, $L_j(\omega)$ are stochastic damages to locations induced by random floods ω, $\omega \in \Omega$, $j = \overline{1:N}$. Constraints (8)-(9) describe stochastic supply-demand insurance relations.

The problem (7)-(9) may be reformulated as

$$\min E\sum_j (1-q_j)L_j + \alpha E \min\{0, \sum_j (q_j L_j - \pi_j)\} + \beta \sum_j E \min\{0, \pi_j - q_j L_j\} \tag{10}$$

where we convert possibly highly discontinuous equations (8)-(9) into expected imbalances defined by convex functions

$$E \min\{0, \sum_j (q_j L_j - \pi_j)\}$$

and

$$\sum_j E \min\{0, \pi_j - q_j L_j\}.$$

Similar to (6), first term in (10) denotes expected uncovered losses, the second is responsible for minimization of insurance premiums and the third term minimizes the expected shortfall of the insurance program on the side of economic agents in each location by minimizing their overpayments.

Adjusting coefficients α and β allows to decrease the expected deficits between insurance supply and demand. They regulate, in a sense, a tradeoff between the level of premiums and the security of the fund. Minimization of function (10) leads to a nonsmooth stochastic optimization problem due to max operations. In the model we assume that catastrophes, i.e., floods, are represented by scenarios $s = \overline{1:S}$, which induce random scenarios of damages L_j^s in locations $j = \overline{1:N}$, with probabilities p_s, $s = \overline{1:S}$. Using S scenarios of HIS-SSM, expressions (8) and (9) are replaced by empirical expectations:

$$\alpha \sum_{s=1}^{S} p_s \min\left\{0, \sum_j (q_j L_j^s - \pi_j)\right\},\ \forall j \tag{11}$$

$$\beta \sum_{s=1}^{S} p_s \min\left\{0, \pi_j - q_j L_j^s\right\} \tag{12}$$

Linearization of (7), (11) – (12) derives the following optimization problem:

$$\min \sum_{s=1}^{S} p_s \sum_j (1-q_j) L_j^s + \alpha \sum_{s=1}^{S} p_s \varepsilon^s + \beta \sum_{s=1}^{S} p_s \sum_j \zeta_j^s \tag{13}$$

s.t.

$$\zeta_j^s \geq 0$$

$\pi_j - q_j L_j^s \le \zeta_j^s$,

$\sum_j (\pi_j - q_j L_j^s) \le \varepsilon^s$,

$\varepsilon^s \ge 0$,

for all scenarios of flood events $s = \overline{1:S}$ in all locations j, $j = \overline{1:N}$. This approach converts non-smooth stochastic optimization under discontinuous constraints into a simple linear optimization problem. There may be considerable uncertainties associated with damage scenarios and flood probabilities, which in the model may be captured by varying probabilities p_s, $s = \overline{1:S}$. For example, it is possible to specify uncertainty bounds for flood return periods, i.e., $s = \overline{1:S}$ $\underline{p}_s \le p_s \le \overline{p}_s$.

4 Numerical experiments: selected results

4.1 Spatial patterns of robust model-derived premiums

In the RD case study region, the robust model-derived (according to (7)-(9)) premiums are computed at the aggregated resolution of 100 by 100 m^2, which approximately corresponds to a block of 16- 25 residential houses. The resolution may be tuned to represent specifics of some areas, e.g., a residential house, a shopping moll, concentrated infrastructure, intensive transportation node. Figure 8 shows spatial distribution of premiums in the case study region aggregated to a neighborhood level and Figure 9 displays premiums as percent of the damages in the 100-year flood.

One may see that while the area is relatively small, there is a big spatial variation among the robust premiums. This implies that robust ICRM-derived premiums capture location-specific risk heterogeneities and, thus, guarantee the stability of the insurance program under conditions that all stakeholders (government, insurance company and households and firms) cover some share of flood risk. For insurance practitioners, the spatial heterogeneity of the premiums highlights the importance of estimating spatially resolved policies. In the majority of neighborhoods, annual insurance premiums average per location (100mx100m cell) do not exceed 5.000 euro for infrastructure, businesses and households. This makes 130-200 euro per property per year excluding premiums for infrastructure. Few neighborhoods, where insurance premiums go up to 50.000-100.000 euro per annum per location, are characterized by high concentration of infrastructure and businesses. Businesses may suffer much larger damages compared to households since in addition to the direct property damage they also incur indirect damage from business interruption.

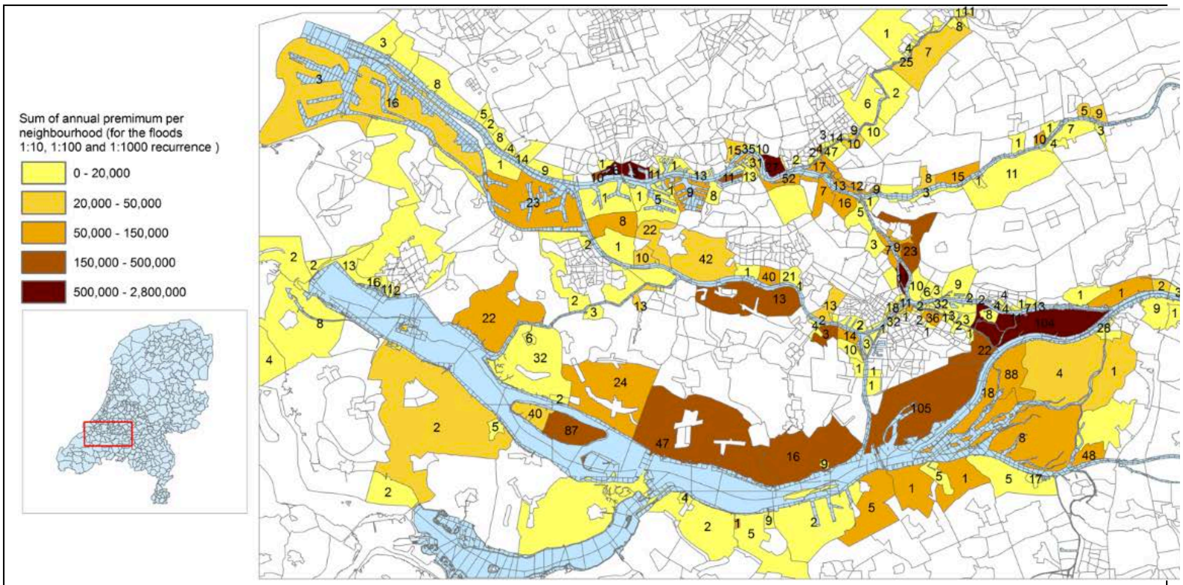


Figure 8: Total sum of robust annual premiums, aggregated per neighborhood (buurt). Number denote the number of affected locations in each particular neighborhood (results have illustrative purpose).

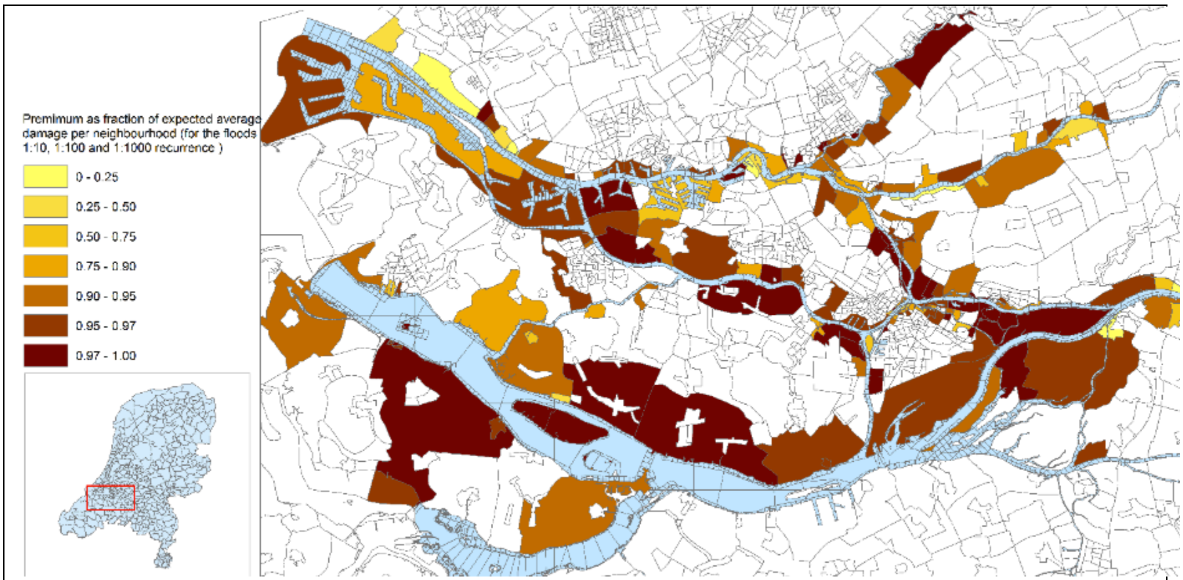
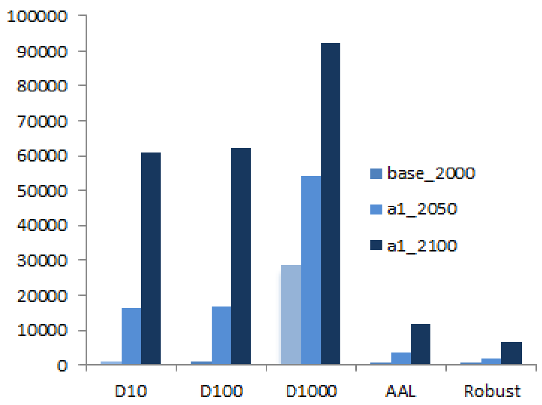


Figure 9: Premiums as percent of the damages in the 100-year flood, aggregated per neighborhood (buurt). Results have illustrative purpose.

Alternative policy options for the choice of premiums can be suggested by stakeholders (i.e., insurers, local governments, individuals). In what follows we discuss with more detail the specifics of robust quantile-based premiums derived by minimization of (7) subject to (8)-(9) and summarize their advantages compared to the AAL premiums. In the outlined numerical experiments we consider the following two rules for calculation of premiums:

1. Quantile-based robust premiums that fairly equalize the risk of instability for the insurance company and the risk of premiums overpayments for exposed individuals (locations);
2. Location-specific premiums based on AAL in a particular location, i.e., actuarial risk-based premiums.



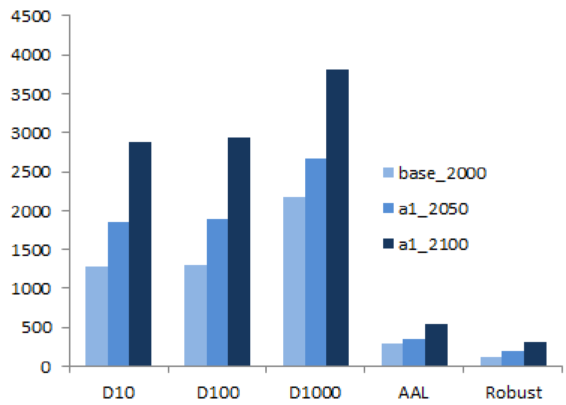


Figure 10.a: **Figure 10.b**:

Flood damages for 3 return periods: D10, D100, D1000 correspond to damages due to 10-, 100-, and 1000- year floods, respectively; and two alternative premium options (per annum) – AAL and Robust (results have illustrative purpose).

Figures 10.a and 10.b show that the robust model-derived premiums are lower than AAL premiums. Thus, the robust premiums not only guarantee financial stability of the insurance program, which involves loss sharing between governments, insurers, and economic agents (households and firms) in flood-prone areas. Quantile-based premiums also reduce insurance prices, what in turn increases attractiveness of the program for economic agents boosting demand for insurance and its take up rates.

Most of the results here are presented on the aggregated level of a neighborhood since the resolution of premium estimate is high while extent of the geographical area of estimation is quite wide. Yet, the ICRM model allows to zoom in and analyze damages, AAL and quantile-based robust premiums for each individual location, i.e. 100m×100m cell. As demonstrated in Figure 11, the spatial differentiation is not only obvious across neighborhoods but also between individual locations. Location to the right exhibits a gradual increase in damages and corresponding insurance premiums (AAL and quantile-based) when moving from 2000 to 2050 and 2100 climate scenario. Location to the left is characterized by more abrupt jumps in damages and corresponding premiums. Note, that for the right location AAL is closer to the robust premium (35 percent difference, current climate estimates) than for the left one (54 percent of difference).

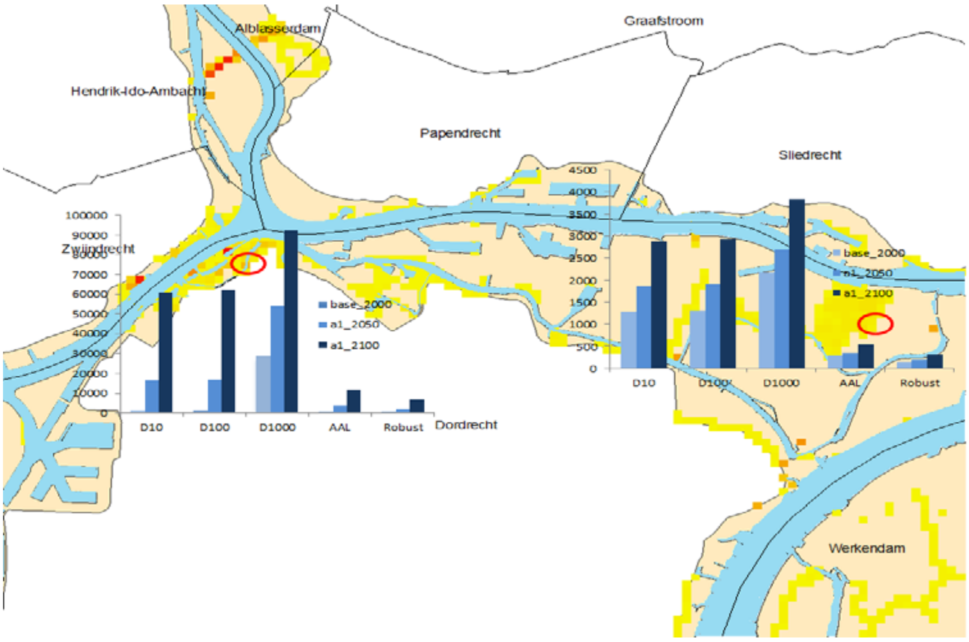
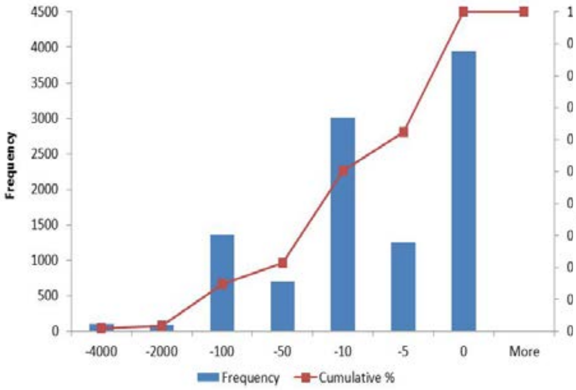


Figure 11: Spatial differences between two representative locations in the case study region: D10, D100, D1000 - flood damages for 10, 100, 1000 year floods; AAL – average annualized premiums based on the average annual damage across 3 flood scenarios; Robust – quantile-based model-derived premiums (results have illustrative purpose).

4.2 Analysis of Optimal Insurance Program per Stakeholder

4.2.1 Analysis of the insurance program financial stability from the insurer side

By varying coefficients α, β it is possible to derive premiums ensuring required solvency for the insurer and desired level of non-overpayments for individuals. Figures 12.a and 12.b present histograms of the indicator $I^1_{j,s} = p_s(\pi_j - q_j L^s_j)$ estimating the balance between premiums paid into and compensations paid out of the insurance fund, for robust and AAL premiums, respectively. Negative values on the horizontal axis identify when compensations exceed premiums, and the vertical axis shows the number of locations. In AAL case (Figure 12.b), compensations are almost always higher than premiums. In Figure 12.a, for robust premiums, the balance is achieved for about 4000 locations (0 on the horizontal axis), while in Figure 12.b, for AAL, only about 1500 locations are in balance.



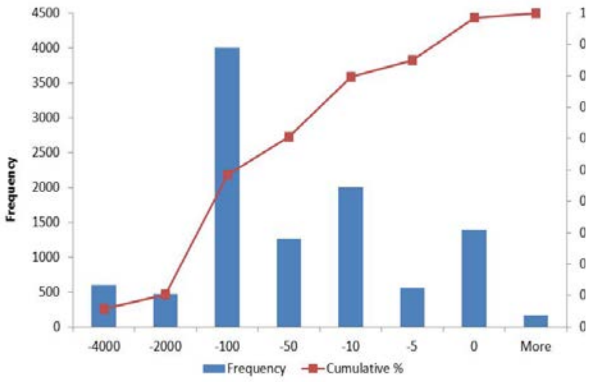


Figure 12.a: Non-overcompensations by insurance companies under robust model-derived premiums

Figure 12.b: Non- overcompensations by insurance companies under annualized premiums based on average damage

Overcompensations increase financial risk to the insurer. Figure 13.a displays a histogram of the indicator $I_s^2 = p_s \sum_j (\pi_j - q_j L_j^s)$, defining insurer's balance between premiums and coverages, $\alpha = 1$, for scenarios $s = 1,2,3$ (i.e., 10-, 100-, and 1000-year floods), respectively. Positive values on the vertical axis mean shortage of the capital. With robust premiums, the insurer has no problems compensating damages from 10-year flood. He experiences only small deficit of the capital reserve in the case of 100-year flood, imbalance between premiums and coverage is about 350.000 euro. In 1000-year flood scenario the insurer may become a bankrupt if he is obliged to fully compensate the damages. In this scenario, capital deficit is about 4,8 mln. euro. In contrast, despite being determined based on the location-specific actual risk (expected average damage), the AAL-based insurance premiums bring the financial stability of the insurance program under questions starting already with less severe 10-year flood. As demonstrated in Figure 2, the annualization of the expected damage omits the facts that coverages need to be paid off instantly at the moment of hazard's occurrence, which in this case causes a shortfall in insurer's fund between 23 mln (for $\alpha = 100$, Figure 13.b) and 25mln euro (for $\alpha = 1$, Figure 13.a) for the 10-year flood scenario. Under the insurance program with robust premiums the financial situation of the insurer is undermined only by 1000-year event, while in the case of AAL-based premiums he is continuously running out of capital (capital deficit).

Insurer's bankruptcy may be avoided completely by adjusting insurer's risk coefficient α. For example, Figure 13 shows financial situation of the insurer if α is changed from 1 to 100. With robust premiums in case of 10-year flood, the insurer accumulates capital surplus of about 200.000 euro indicated by the negative value in Figure 13.b (marked with "10-yr" on the horizontal axis). The insurer's reserve is still positive in case of 100-year event, and only 1000- year event leads to about 1,25 mln euro capital deficit.

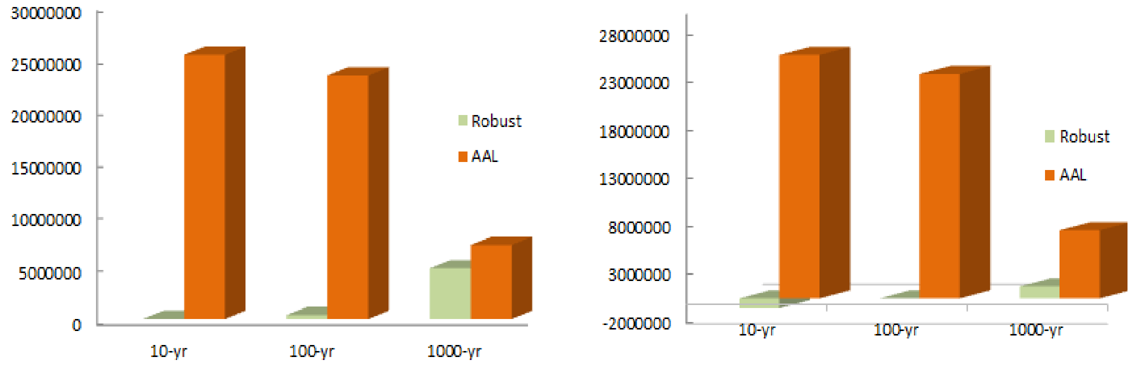


Figure 13: Insurer's balance between premiums and coverages: for Robust and AAL premiums,

13.a: $\alpha = 1$ **13.b:** $\alpha = 100$

4.2.2 Analysis of the insurance program financial stability from households and firms side

Changing α from 1 to 100 increases premiums and changes the profile of the indicator $I^1_{j,s}$ as in Figure 14a,b. In particular, Figure 14b shows that robust premiums derived with $\alpha = 100$ almost fairly balance out the overpayments and underpayments of individuals, i.e., the number of negative and positive values of $I^1_{j,s}$ is approximately the same. Further increase of α would lead to complete safety of the insurer, e.g., no capital deficit even in the most severe 1000- year catastrophe, however for the cost of higher premiums, which may reduce insurance demand.

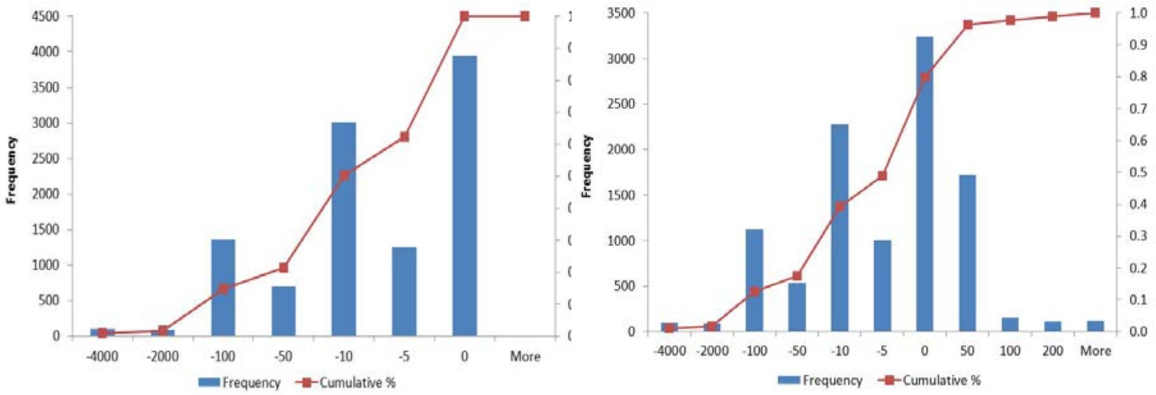


Figure 14: Non-overpayments by economic agents (firms and households)

14.a: robust premiums, $\alpha = 1$.

14.b: robust premiums, $\alpha = 100$.

4.2.3 Analysis of the insurance program stability from the government perspective

Apart from premiums, the model provides insights regarding initial risk reserve, necessary amount of reinsurance or governmental compensation, or other financial instruments such as contingent credit or bond. By varying risk coefficients α and β it is possible to analyze optimal combination of different financial instruments and study their role in flood insurance system. Botzen and van den Bergh (2008) provide arguments in favor of a public-private "three-pillar" flood insurance system in the Netherlands. Similar type of public-private-civil partnerships have already been studied in US [33], Italy, Hungary [20], etc.

In the three-layered system, the first layer may assume the government, which would provide compensation of a limited amount to all households that suffer losses from flooding. As the second layer, a private insurance (or local mutual catastrophe fund) may be established by pooling risks through flood insurance on the basis of location-specific risk exposures. As the third layer, a contingent credit may become available to provide an additional injection of capital to stabilize the system.

For the analysis of the three-pillar system, the goal function (7) may be formally modified as follows: minimize

$$E\sum_j (1-q_j)L_j(\omega) + E\sum_j \nu L_j(\omega) \tag{14}$$

under constraints (8)-(9), where ν is a level of governmental compensation, $q_j + \nu \le 1$, $j = \overline{1,N}$. The evaluation of optimal robust governmental share ν requires explicit introduction of the governmental (catastrophe) budget and its insolvency constraint similar to (8)-(9). The size of this budget is itself a key decision variable, which calls for essential modifications of the model and is not considered in these studies. In fact, the choice of ν may substantially depend on stake holders opinion and therefore be defined exogenous as in these illustrative experiments where we assume $\nu = 0$. The sensitivity analysis with respect to varying ν is rather straightforward and is not the subject of the current discussion.

The demand for contingent credit is defined by the indicator $I_s^2 = p_s \sum_j (\pi_j - q_j L_j^s)$ reflecting capital deficit of the insurer. Thus, in Figure 13a,b, with $\nu = 0$, the demand for contingent credit is shaped by positive values of the I_s^2, i.e., the histogram of insurer's shortfall. It is possible to reshape the risk of the insurer by altering the assumption about risk coefficients α and β and the level of governmental support ν.

5 Conclusions

This paper discusses the importance of properly designed financial arrangements for sharing flood losses while comparing insurance premiums estimated based on average annual damage vs. quantile-based premiums. We presented an illustrative example of robust insurance program for a case study region close to Rotterdam in the Netherlands. We consider a loss-sharing program based on pooling flood risks through private flood insurance, partial compensation to the flood victims by the central government, and a contingent credit to the insurance for "buffering" the risk. The success of this program depends on the mutual stability of the involved stakeholders. For the analysis of the stability, we use the ICRM approach allowing to derive robust insurance policies, e.g., premiums and coverage of the insurer, governmental support, involvement of individuals, accounting for complex interplay between multivariate spatially and temporally explicit probability distributions of flood losses and risk exposures of the stakeholders. A robust policy satisfies two goals: (i) to fulfill goals and constraints of the involved stakeholders, and (ii) to guarantee program's solvency under all (or a percentile) flood scenarios rather than one (average) event

In the case study region, the ICRM is comprised of a geographically-detailed updated HIS-SSM model and of a spatially-explicit quantile-based multi-agent multi-criteria stochastic optimization (STO) procedure integrated as follows: (1) water depth levels are processed in HIS-SSM to calculate flood damages for 10-, 100-, and 1000- year floods; (2) STO estimates robust policies fulfilling the safety requirement of the program.

With numerical experiments, we compare two alternative ways of calculating insurance premiums: the robust derived with ICRM and the AAL approaches. In case of catastrophic flood losses, which occur as "spikes" in time and space, the AAL approach does not guarantee proper balance between premiums and claims, and the insurer experiences deficit of the capital to cover the losses. With robust premiums, the insurer is better off.

We argue that because of significant interdependencies among catastrophe losses across different locations, the demand for a particular financial instrument cannot be separated from the demand for other risk transfer and risk reduction measures. In particular, our numerical experiments show that robust location-specific premiums of the insurance decrease the demand for contingent credit, as discussed in Section 4.2.3. Section 4.2.2 explains how ICRM allows tuning of robust premiums towards the required trade-off between the level of insurer solvency and the overpayments by the individuals, thus increasing popularity of the insurance and its take up rates. One of the future directions for the ICRM approach would be to consider a coupled choice of financial loss sharing measures among stakeholders and structural flood mitigation measures, such as zoning of certain land use functions, elevation of an area or particular buildings, wet and dry floodproofing [12].

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