MILLIMAN REPORT

Flood risk modelling in Europe

Projecting insured losses in the Netherlands and France for varying climate scenarios, using open data

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Table of contents

EXECUTIVE SUMMARY ... **1**
- GOAL OF RESEARCH ... 1
- APPROACH AND DATA ... 1
- RESULTS AND CONCLUSIONS ... 1

FLOOD RISK IN EUROPE ... **4**

APPROACH ... **6**

KEY VARIABLES EXPLAINING FLOOD DAMAGE ... **7**
- FLOOD RISK CHARACTERISTICS ... 7
- PREVENTIVE SYSTEMS ... 7
- BUILDING MATERIALS ... 8

DATA AND ASSUMPTIONS ... **9**
- PORTFOLIO VARIABLES ... 9
  - Portfolio composition – France ... 9
  - Portfolio composition – the Netherlands ... 10
  - Rebuild value ... 11
  - Risk characteristics ... 12
  - Differences between catastrophe tool and scenario Analysis tool ... 12
  - Flood hazard characteristics ... 13
  - Flood hazard characteristics data selected for the scenario analysis tool ... 14
  - Territory characteristics ... 15
  - Protection levels ... 16
- LOSS FUNCTION ... 17
  - Depth-damage function ... 17

RESULTS AND COMPARISON ... **18**
- FRANCE ... 18
- THE NETHERLANDS ... 20
- COMPARISON ... 22

KEY TAKEAWAYS ... **23**

ADDITIONAL RESEARCH ... **23**

APPENDICES ... **24**

APPENDIX A – RESULTS ANALYSIS ... **24**
- FRANCE ... 24
- THE NETHERLANDS ... 26

APPENDIX B – DETAILED APPROACH ... **29**
- GENERAL APPROACH ... 29
- SCENARIO ANALYSIS TOOL ... 29
- CATASTROPHE TOOL ... 30

Executive summary

GOAL OF RESEARCH

Flooding, a pervasive natural hazard across Europe, stems not only from persistent precipitation, locally or upstream of rivers, but also from sea or groundwater sources. The flood risk at any given location encapsulates both the probability of a flood event and the potential for property and economic damage. Human development can either mitigate or exacerbate this risk.

Flooding can inflict extensive damage on homes and infrastructure. Moreover, climate change is predicted to escalate both the severity and frequency of European floods, as heavy rainfall events and snow melt are anticipated to become more frequent and intense.[1] Recent history has indeed witnessed a surge in flood events across Europe.[2]

The goal of this report is to present a comprehensive framework for calculating potential home insurance losses from European flood events based on open data sources. This framework leverages data on portfolio information, climate conditions, and protection levels. We have incorporated two distinct tools. The first tool (catastrophe tool) offers valuable insights into catastrophe risk by evaluating the impacts of floods with varying return periods (for example, one-in-100-year flood depth events), based on current climate and protection levels. The second tool (scenario analysis tool) facilitates scenario analysis, providing insights into the long-term effects of different climate scenarios and protection levels. As both tools leverage open data sources, they are cost-effective alternatives to commercially available catastrophe or scenario models. Both approaches can be used in risk assessment, such as solvency II ORSA (Own Risk and Solvency Assessment), as well as a basis to further develop pricing or risk models.

This framework and its associated tools can be effectively applied to real-world insurance portfolios in any European nation, or even globally where existing public flood risk data is available. Additionally, the results could prove beneficial for other stakeholders, including banks, municipalities, and other government agencies.

APPROACH AND DATA

The general approach taken in this report is to map notional portfolio information (addresses and proxied rebuild values of dwellings) to flood depth data and apply a depth-damage function to obtain insured losses. This general approach is independent of the underlying data; however, implementation may depend on the actual data that is available for a given geography or portfolio. For this research, we have used open data sources for the notional portfolio information, risk characteristics such as flood hazard data, territory characteristics and protection levels and the depth-damage function.

The notional portfolios are obtained by sampling from address registers in France and the Netherlands, while properties needed to proxy a rebuild value are obtained from governmental registrations as well. The data on flood hazards and protection levels stem from local governmental organizations for the current risk situation, and from academic research when taking into account the potential impact of climate change. Where needed, up sampling of the data is performed to improve the resolution of the flood risk data, for more reliable results. This is achieved by overlaying the lower granularity flood risk map with a high granularity elevation map, to incorporate the effects of relative elevation. Lastly, the depth-damage function used comes from research performed by the Joint Research Centre of the European Commission.

RESULTS AND CONCLUSIONS

Both tools have been applied to notional portfolios of insurers in France and the Netherlands. See Figure 1 for an overview of the cost per region for varying likelihood of riverine and coastal flood events. Note that in some regions no events occur. However, this analysis does not include pluvial flooding, which might also impact those unaffected regions.

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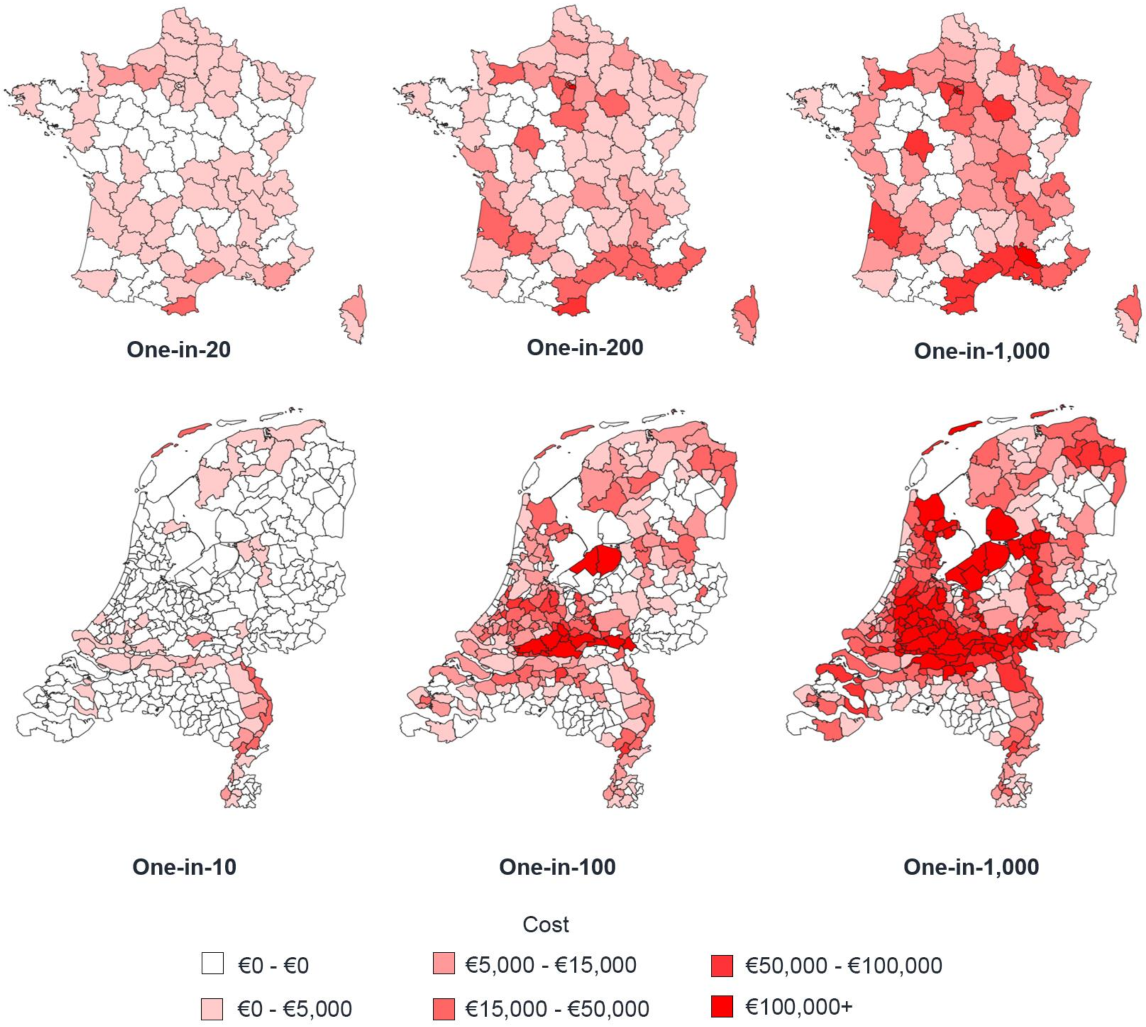
[1] International Panel on Climate Change (2022). Climate Change 2022: Impacts, Adaptation and Vulnerability – Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Chapter13: Europe. Retrieved from https://www.ipcc.ch/report/ar6/wg2/downloads/report/IPCC_AR6_WGII_Chapter13.pdf.

[2] Paprotny, D., Sebastian, T., Morales Napoles, O., & Jonkman, B. (2018). Trends in flood losses in Europe over the past 150 years. Nature Communications, 9(1), Article 1985. Retrieved from https://doi.org/10.1038/s41467-018-04253-1.

FIGURE 1: AVERAGE COSTS PER INSURED ADDRESS OF COASTAL AND RIVERINE FLOOD EVENTS WITH DIFFERENT PROBABILITY PER DEPARTMENT (FRANCE) AND MUNICIPALITY (THE NETHERLANDS) USING CATASTROPHE TOOL.



Data sources used: portfolio information as in sections “Portfolio composition – France” and “Portfolio composition – the Netherlands”, flood hazard data as in section “Flood hazard characteristics data selected for catastrophe tool”

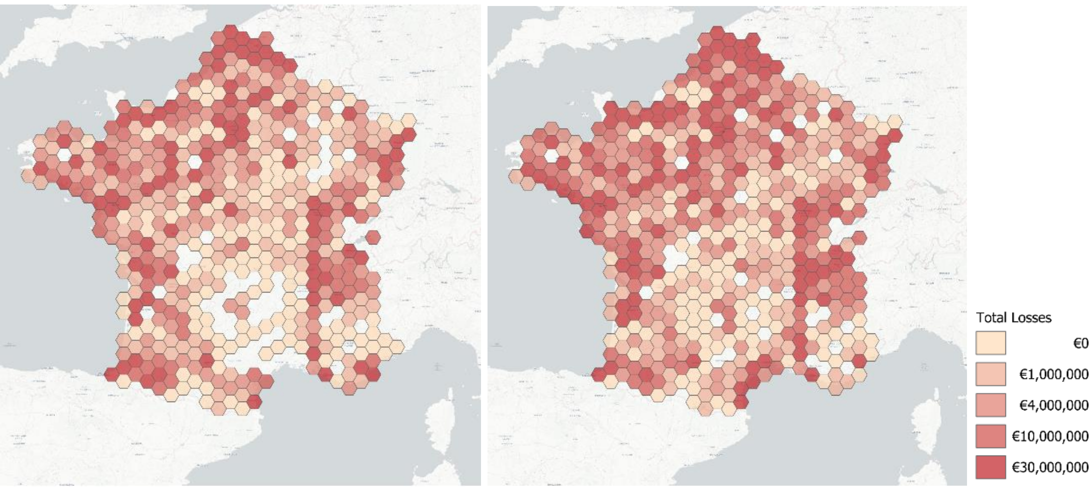
When including the impact of varying climate scenarios, it can be seen in Figure 2 that in scenarios with continued high greenhouse gas (GHG) emissions the possible losses in the French and Dutch notional portfolios (depicted as percentage of total insured amount) are higher than in a scenario where GHG emissions are reduced extensively. Furthermore, the level of flood protection assumed drastically impacts the losses as well. The figure shows the annualized losses as a percentage of the insured amount for two protection levels. A protection against all events which have a one-in-100-year likelihood of occurring based on historical data and numbers that follow from current protection standards. The latter is based on an international database of protection standards per region (FLOPROS). As the figure shows, for France this leads to higher losses, whilst for the Netherlands it leads to a decrease. This implies that for France, at least in some regions, the protection standards do not protect against one-in-100-year events, whilst in the Netherlands the protection standards are better than one-in-100-years.

FIGURE 2: ANNUALIZED LOSSES PER EUR 1,000 INSURED AMOUNT FOR BOTH NOTIONAL PORTFOLIOS OVER PERIOD 2024-2060 – SCENARIO ANALYSIS TOOL

	PROTECTION 1-IN-100		FLOPROS PROTECTION	
RCP SCENARIO	LOSS PER EUR 1,000 INSURED AMOUNT - FR	LOSS PER EUR 1,000 INSURED AMOUNT - NL	LOSS PER EUR 1,000 INSURED AMOUNT - FR	LOSS PER EUR 1,000 INSURED AMOUNT - NL
RCP2.6	1.5	2.1	1.8	0
RCP6.0	3.0	5.0	3.7	0
RCP8.5	3.8	12.4	4.6	0

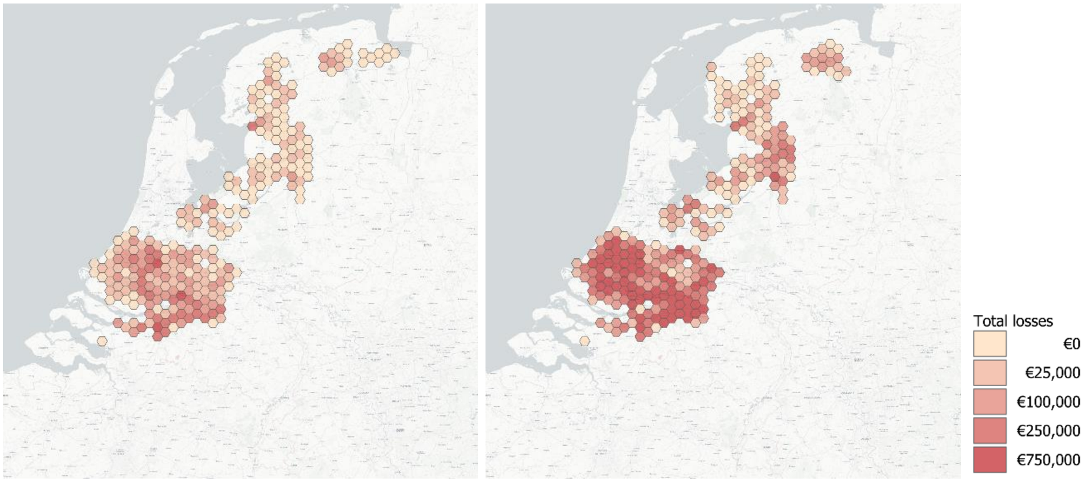
Figure 3 and Figure 4 below show how the total losses in the French and Dutch notional portfolios are distributed across the respective countries for the different RCP scenarios.

FIGURE 3: TOTAL LOSSES IN THE FRENCH PORTFOLIO FOR RCP 2.6 (LEFT) AND RCP 8.5 (RIGHT) SCENARIO OVER PERIOD 2024-2060 (IN HEXAGONS OF 50X50 KM), ONE-IN-100 PROTECTION USING SCENARIO ANALYSIS TOOL.



Data sources used: portfolio information as in section “Portfolio composition – France”, flood hazard data as in section “Flood hazard characteristics data selected for scenario analysis tool”

FIGURE 4: TOTAL LOSSES IN THE DUTCH PORTFOLIO FOR RCP 2.6 (LEFT) AND RCP 8.5 (RIGHT) SCENARIO OVER PERIOD 2024-2060 (IN HEXAGONS OF 10X10 KM) , ONE-IN-100 PROTECTION USING SCENARIO ANALYSIS TOOL.



Data sources used: portfolio information as in section “Portfolio composition – the Netherlands”, flood hazard data as in section “Flood hazard characteristics data selected for scenario analysis tool”

From the numbers and maps above, it can be concluded that the extent to which results change in different scenarios can vary across the countries considered. Hence, local expertise is paramount in interpreting the outcomes.

Flood risk in Europe

There are four main types of flooding.[3] First, slow lowland floods: these are fairly common. They are often predictable, as they follow long periods of rainfall in rivers that are already high. Then there are rapid, torrential floods: These can cause flash floods with potentially devastating consequences, including loss of life. Rising water levels can be very rapid and less predictable. Runoff flooding occurs when rainfall cannot or no longer infiltrate the ground. Water then runs off in areas that are usually dry. Finally, marine flooding is the rapid, short-term inundation of coastal areas by the sea during adverse weather and ocean conditions. This report looks specifically at fluvial and coastal floods; flash floods are left out of consideration.

All types of flooding can result in extensive damage to homes and infrastructure. In addition, climate change is projected to increase the magnitude and frequency of floods in Europe, as the frequency and intensity of heavy rainfall events are projected to increase in the future.[4] In recent history, an increasing trend in the amount of flood events in Europe has been observed.[5]

The 2021 floods in Belgium, Germany and the Netherlands resulted, for instance, in extensive damage to homes and infrastructure. The damage in the Netherlands was concentrated in the southern province Limburg. Even though the type of river flood that occurred was not insured under most Dutch policy conditions at that time, most insurance companies were lenient in their application of the conditions and settled large parts of the losses. The insured losses totalled €211 million in the Netherlands only.[6] In December 2023, the river IJssel reached water levels that caused minor flooding in Deventer,[7] a city with around 100,000 inhabitants. Also in the late fall of 2023, the river Waal reached near-flood water heights around the city of Nijmegen, a city populated by almost 200,000 persons, causing the streets close to the river border to be closed for traffic.[8]

In France, 'flood risk is the leading natural hazard in terms of the extent of the damage it causes, the number of municipalities affected, the extent of flood-prone areas and the populations living in these areas.'[9] Several examples of extreme flooding support this observation: In the French region Hauts-de-France, for example, there have been two very close to one-in-100-year floods. The first one occurred in November 2023, with an estimated cost of €550 million by the Caisse centrale de réassurance (CCR). The second occurred in January 2024, estimated at €90 million.[10]

Events like the above illustrate that floods form a material risk for European countries. Adaptation measures, such as early warning systems, evacuations, insurance and flood retention strategies can help reduce or mitigate the risks associated with flooding. However, the effectiveness of these measures may vary across different regions, and flood events may occur regardless. Therefore, it is important for consumers and companies to be aware of this risk and to be properly insured. Regulation can help, both to encourage insurance and to make insurance affordable, for instance through public-private partnerships. In the Netherlands, for example, the Association of Insurers is working with the government to find ways to insure flood losses from primary river barrier breaks,[11] in addition to insurance for secondary barrier breaks, which have been largely included in policy conditions in the years 2021 and 2022.

[3] Géorisques, République Française. Inondation: Le premier risque naturel en France. Retrieved from https://www.georisques.gouv.fr/minformer-sur-un-risque/inondation.

[4] International Panel on Climate Change (2022). Working Group II Contribution to the Sixth Assessment Report . Chapter13: Europe. _

[5] Paprotny, D., Sebastian, T., Morales Napoles, O., & Jonkman, B. (2018). Trends in flood losses in Europe over the past 150 years. Nature Communications, 9(1), Article 1985. Retrieved from https://doi.org/10.1038/s41467-018-04253-1.

[6] Verbond van Verzekeraars. Overstroming en droogte. Retrieved from https://www.verzekeraars.nl/verzekeringsthemas/klimaatbestendig-nederland/overstroming-en-droogte.

[7] NOS (December 2023). Noodplan in werking in Deventer: IJssel bereikt kademuur, overstroming dreigt. Retrieved from https://nos.nl/regio/overijssel/artikel/471868-noodplan-in-werking-in-deventer-ijssel-bereikt-kademuur-overstroming-dreigt.

[8] De Gelderlander. Waalkade door hoogwater weer afgesloten oekrainers via steigerbrug van en naar opvangschepen. Retrieved from https://www.gelderlander.nl/nijmegen/waalkade-door-hoogwater-weer-afgesloten-oekrainers-via-steigerbrug-van-en-naar-opvangschepen~a3946588/.

[9] Géorisques, République Française. Dossier expert sur les inondations. Retrieved from https://www.georisques.gouv.fr/consulter-les-dossiers-thematiques/inondations.

[10] L'Argus de l'assurance. Inondations dans les Hauts-de-France: Facture révisée à la hausse pour l'épisode de novembre. Retrieved from https://www.argusdelassurance.com/green-assurance/inondations-dans-les-hauts-de-france-facture-revisee-a-la-hausse-pour-l-episode-de-novembre.230162.

[11] Verbond van Verzekeraars. Insurers take next step in insuring flooding by large river or sea. Retrieved from https://www.verzekeraars.nl/en/publications/news/insurers-take-next-step-in-insuring-flooding-by-large-river-or-sea.

This raises the question of how to anticipate the costs of flood damage, including the uncertain impacts of climate change. Indeed, insurers need to know how their portfolio's exposure to risk is evolving, in order to better protect their policy holders, price their products and anticipate future claims. But also other organizations, like banks, municipalities and other government agencies, will be affected by flood damage and will need to assess their risks.

This report introduces a framework for projecting flood-related costs of private home insurance portfolios, specifically for damage to dwellings, based on open data sources. This framework has been effectively implemented across two distinct models, allowing for a comprehensive and adaptable approach to risk management. One implementation can be used as a catastrophe tool to gain insight on flood risk for different likelihood of events over a short time horizon, while the other implementation can be used to investigate the impact of different climate scenarios and future protection levels on flood risk. Given that these approaches leverage on open data, they present cost-effective alternatives to commercially available catastrophe models, and allow for forward-looking scenario testing. Both approaches can be used in risk assessments, such as Solvency II ORSA (Own Risk and Solvency Assessment). as well as a basis to further develop pricing or risk models.

This report starts off by presenting the overall structure of the flood risk framework. The second part is devoted to literature research, describing on a high level the various factors that influence property damage following a flood. In the following section, the data and assumptions used within the framework are explained. Here also the differences between the two implementations are highlighted. Finally, the two implementations are each tested on two countries, France and the Netherlands, and the results are compared.

This study focuses on the impact of flooding on home insurance claims (damage to dwelling), from flood events that follow from river overflow and coastal flooding. The data employed comes from various European sources. In this report, the two implementations are applied to notional portfolios in France and the Netherlands. However, the study is easily applicable to real-life insurance portfolios or other exposure measures, and to any other country in Europe or even other global regions.

Approach

Two frameworks have been developed as part of this research. Some differences exist between the two frameworks, which are discussed in the section Data and Assumptions. However, they both follow the same logic.

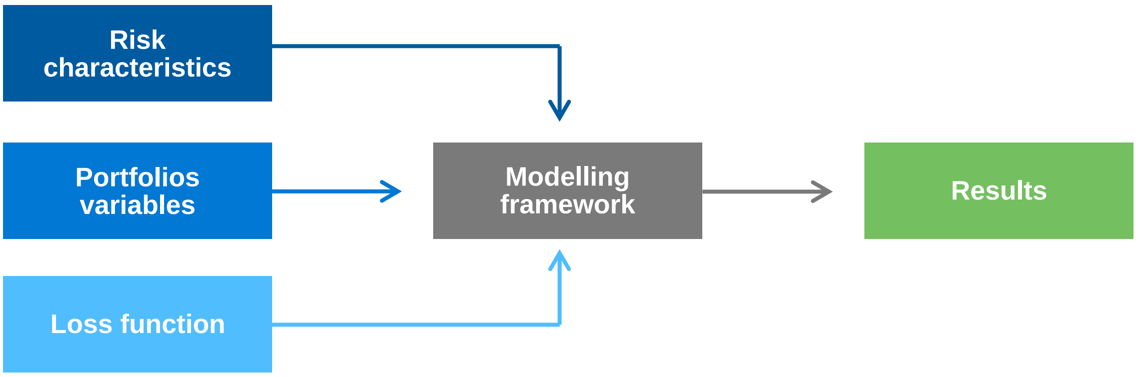
Apart from the data that is used, the difference in practical use between the two implementations is that one allows for processing of multiple climate scenarios. The other tool is suitable to assess the impact of (extreme) flood events with different likelihood, based on the current state of the climate. Hence, we will refer to the first implementation as 'scenario analysis tool' and to the second implementation as 'catastrophe tool.'

For both frameworks, three types of inputs are required:

- Portfolio variables describing the insured assets, i.e., the type of buildings insured, their location and their rebuild value
- Risk characteristics of the floods, i.e., flood depths per location in a certain climate scenario
- A loss function combining the portfolio variables and the risk characteristics into a financial loss

The output of the model is an estimate of the possible flood-related loss for a given insurance portfolio and a given climate scenario.

FIGURE 5: OVERVIEW OF THE MODELLING APPROACH



The loss function, input data, and assumptions used with regard to the portfolio variables and risk characteristics are extensively discussed in the upcoming sections.

See Appendix B for a detailed description of the approach, including the differences between the catastrophe tool and the scenario analysis tool.

Key variables explaining flood damage

FLOOD RISK CHARACTERISTICS

Several parameters characterize the severity of a flood,[12] and in particular the damage to real estate and personal property.

First of all, the height of the water (i.e., the flood depth) is a very, if not the most, important parameter. The higher the water rises, the more pressure it exerts on the walls, and the greater the risk of damage to the building's structure. Damage is not proportional to the height of water in a linear way, but rather evolves by steps. The first step concerns the baseboard level, where, if this threshold is not exceeded, damage is mainly seen to floors and coverings. The second threshold is at the bottom of the window, where electrical outlets, walls and wall coverings are located. Third, the ceiling level is important. At that point almost the entire building, including glazing, light fittings, electrical and heating installations is affected. Finally, if the next floor is reached, the damage extends to the electrical components and pipes that run between the ground floor and the first floor. The situation then repeats for any additional floors present in the building.

The second important characteristic is immersion time. The longer the water remains, the more a building will be damaged, because the water will penetrate the materials, and the moisture will soak into the walls and claddings, causing them to swell, deform or even be destroyed. Of course, this depends on the building materials used.

Then, the speed of the current can also increase the damage. A fast current could erode the ground at the foundation level, causing the building to collapse or subside. Current can also cause damage by projecting heavy objects into the building.

Finally, turbidity (the presence of fine clay or silt particles suspended in the water) and water pollution (the presence of pollutants such as hydrocarbons) can aggravate the damage, as these particles and products impregnate the walls and damage them over the long term, while giving off strong smells.

While the first two characteristics (water height and duration of immersion) may be available in open data, a database listing the speed of the current, turbidity, and water pollution for flooding events has not been found for this study.

PREVENTIVE SYSTEMS

There are three strategies that can be adopted when faced with the risk of flooding: Avoid, Resist or Yield to water.[13]

The first strategy, Avoid, is considered the most efficient and cost-effective, since it avoids, as its name suggests, any damage caused by water. This strategy involves raising the structural elements of the building, such as building on stilts, using raised embankments, creating floating buildings (the buildings are built on floats), or creating a crawl space, or an unburied garage, on the ground floor, which raises the second floor. This strategy is mainly used on new buildings in flood-prone areas.

The variables to collect to anticipate flood damage would therefore be the existence of these building elevation measures. This is information that insurers do not generally collect from policyholders as part of the underwriting process, while it is even unclear whether policy holders are aware of it themselves. So, in order to incorporate this data it is likely that public resources would need to be exploited. For this report, building elevation measures have not been included.

The second strategy, Resist, is also intuitive and widespread. It consists of installing devices that will limit the penetration of water into the building to reduce damage. This strategy proves its worth when the water level is no more than one meter high, the flood lasts no more than two days, and there is sufficient time to allow residents to put the various devices in place.

[12] Centre Européen de Prévention du risque d'Inondation (March 2010). Le bâtiment face à l'inondation: Vulnérabilité des ouvrages. Retrieved from https://www.cepri.net/tl_files/pdf/aidememoire.pdf.

[13] Observatoire de l'immobilier durable (OID). Guide des actions adaptatives au changement climatique: Le bâtiment face aux aléas climatiques. Retrieved from https://www.actu-environnement.com/media/pdf/news-37314-oid-guide-adaptation-batiments-changement-climatique.pdf p.70.

Here are a few examples of such devices:

- Installing non-return valves on sewage and rainwater drains to prevent sewage from flowing back into the building
- The installation of fixed or removable cofferdams
- It is also possible to build a low wall around the building to protect walls and openings from the force of the current

The existence of these devices is generally not known to the insurer, partly because this information is not usually requested at this stage by underwriters, and partly because this data does not exist in open data.

The third strategy is to 'give in' to the rising water. Knowing that the ground floor is going to be flooded, one would act accordingly: choice of robust building materials and installation of living spaces on the upper floors, not on the ground floor—and the same applies to electrical equipment.

A final option would be to abandon the risky areas and move to zones which are less likely to flood, e.g., a 'managed retreat' strategy. Even though this is usually a last resort option, it can also be seen as a powerful adaptation strategy.[14]

BUILDING MATERIALS

Finally, the last variables that have material influence on the extent of flood damage are those relating to building materials. In fact, the damage caused is a function of the type of building materials and the characteristics of the flood. The European Flood Risk Prevention Centre, in conjunction with insurance and construction experts, has drawn up a table detailing, for each building element, the nature of the potential damage and the probability of this damage, depending on the materials used, the height of water and the duration of immersion.

FIGURE 6: EXTRACT FROM THE TABLE OF LOSS PROBABILITIES ACCORDING TO IMMERSION TIME, WATER HATER AND TYPE OF MATERIAL

WORK	WORK DESCRIPTION			NATURE OF POTENTIAL DAMAGE	PROBABILITY OF DAMAGE (%)			INCIDENCE H
	PART OF THE WORK	CHARACTERISTICS	MATERIALS		<0.5 DAYS	2 TO 3 DAYS	>3 DAYS	H (METERS)
Interior wall coverings	On plaster, walls or doors		Paper	Degradation, delamination, indelible stains	75	100	100	H>0.1
			Paint	Degradation, delamination, indelible stains	50	75	100	
			Textile	Degradation, delamination, indelible stains	75	100	100	
			Wood	Delamination, swellings	10	50	100	
			Glued tiles	Delamination	0	0	100	H>ground
			Sealed tiles	No damages	0	0	0	NA
Floors	Top of crawl space, top of basement, top of first floor	Full tile	Concrete	No damages	0	0	0	NA
		Beams and slabs	Concrete	No damages	0	0	0	NA
		Joists and stringers	Metal and bricks	Swelling and degradation	0	0	5	H>ground
		Joists and panels	Wood	Swelling and deformations	25	75	100	H>ground

Source: le bâtiment face à l'inondation – Diagnostiquer et réduire sa vulnérabilité. CEPRI[15]

Note that most of this information is not available as open data; hence this is not included in our report. Furthermore, insurers currently do not request this information during the underwriting process, which means that also in practice building materials information will be difficult to incorporate.

[14] Zurich (May 2023). Is managed retreat a viable response to climate risk? Retrieved from https://www.zurich.com/en/knowledge/topics/climate-change/is-managed-retreat-a-viable-response-to-climate-risk.

[15] https://www.cepri.net/tl_files/pdf/aidememoire.pdf

Data and assumptions

This section is dedicated to the description and justification of the data and assumptions chosen for the modelling framework. This concerns portfolio variables, such as the composition of the addresses to include in our notional portfolios and characteristics necessary to calculate the rebuild value. Also risk characteristics are discussed, such as the climate scenarios and prevention and protection measures which are incorporated to generate flood events. For the risk characteristics a distinction is made between the catastrophe tool and the scenario analysis tool. These differences are highlighted in this section as well.

PORTFOLIO VARIABLES

The modelling framework is designed so that a large part of the model's input is data from a portfolio of policyholders. This concerns addresses and rebuild values. For an insurer this is ideally information from its own portfolio, or rebuild values can be estimated using own claims data. However, in the context of this study, external data from reliable open data sources is used. Two notional portfolios are set up: one for France and one for the Netherlands.

Portfolio composition – France

The French portfolio is aimed to be a representative housing portfolio of a rural insurer. For dwellings with fewer floors, floods will likely carry a higher risk (relative to the total building value) than for apartment buildings, where the higher floors are less likely to be affected. We have therefore chosen to build up our portfolio of mainly rural dwellings (houses of at maximum two floors), which is representative for a portfolio of a rural insurer.

To do so we identified key variables describing insured housing: policy location, area, number of floors, floor for a flat, insured value and presence of protective equipment. An open data source provides some of these key variables on the French territory: the CSTB (Scientific and Technical Centre for Building) with the BDNB (Database for Buildings).

The BDNB has the advantage of providing the type of accommodation: individual or multi-unit building. Therefore, we build our notional portfolio with data extracted from the BDNB.

FIGURE 7: DATA SOURCES BUILDING CHARACTERISTICS FRANCE

CHARACTERISTIC	DATA SOURCE
Geolocation (policy location)	Base Nationale des Bâtiments (BDNB) du CSTB
Building information (height, footprint, wall materials…)	Base Nationale des Bâtiments (BDNB) du CSTB
Building type (house or flat, floor)	Base Nationale des Bâtiments (BDNB) du CSTB

The extraction is done with Python and aims to have more individual houses than multi-unit buildings, to be representative of a rural insurer as explained before. The first portfolio extracted from the BDNB represents 100,000 accommodations throughout mainland France with 73% of individual houses (it should be noted that at national level there are 56% of individual houses[16]).

Figure 8 represents a description of some accommodations, sampled from the notional portfolio. The policy location is not included on purpose because it is a geometric shape representing the building and cannot be written in a consistent manner.

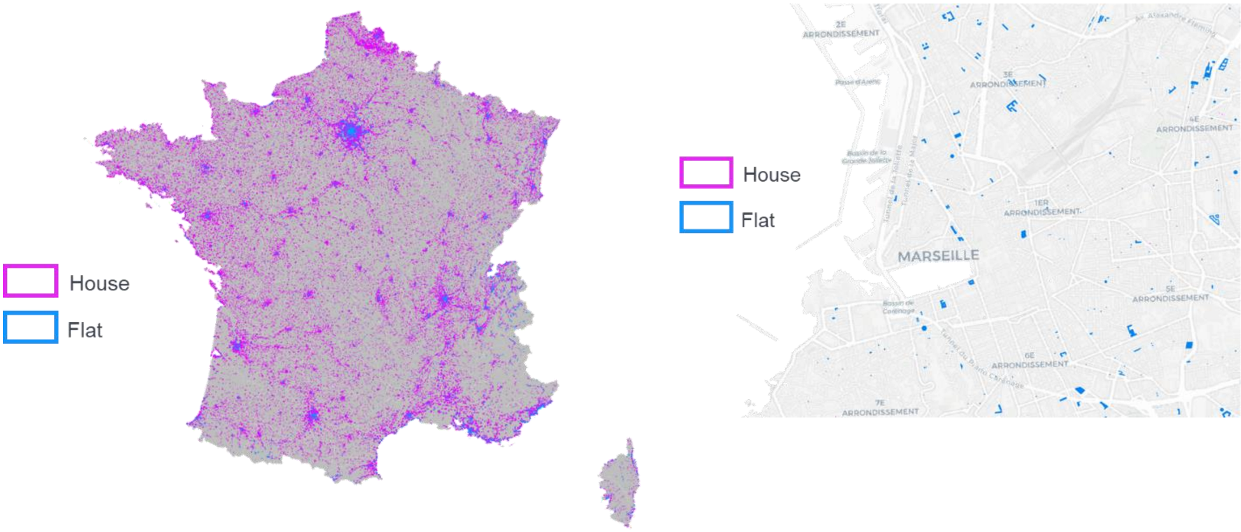
FIGURE 8: SAMPLE CHARACTERISTICS OF BUILDINGS IN FRENCH NOTIONAL PORTFOLIO

ID	HOUSING SURFACE AREA (M²)	BUILDING HEIGHT (M)	FLOOR	WALL MATERIALS
0	18	19	4	Concrete
1	120	3	0	Chipboard
2	86	5	0	Brick

[16] Institute national de la statistique et des études économiques. Parc de résidences en habitat collectif ou individuel: Données annuelles do 2004 à 2003. Retrieved on April 16, 2024 from https://www.insee.fr/fr/statistiques/2412780#tableau-figure1

The locations of the notional portfolio are shown in Figure 9, including a focus on Marseille.

FIGURE 9: NOTIONAL PORTFOLIO FOR FRANCE AND FOCUS ON MARSEILLE USING POSITRON



Data sources: see Figure 7.

To test the model and assess performance, two other notional portfolios are created by extracting respectively 10 thousand and 1 million addresses from the BDNB as described above. The performance assessment is documented in the section Results and comparison.

Portfolio composition – the Netherlands

For the notional portfolio in the Netherlands the characteristics of the buildings in the portfolio are extracted from the following data sources:

FIGURE 10: DATA SOURCES BUILDING CHARACTERISTICS THE NETHERLANDS

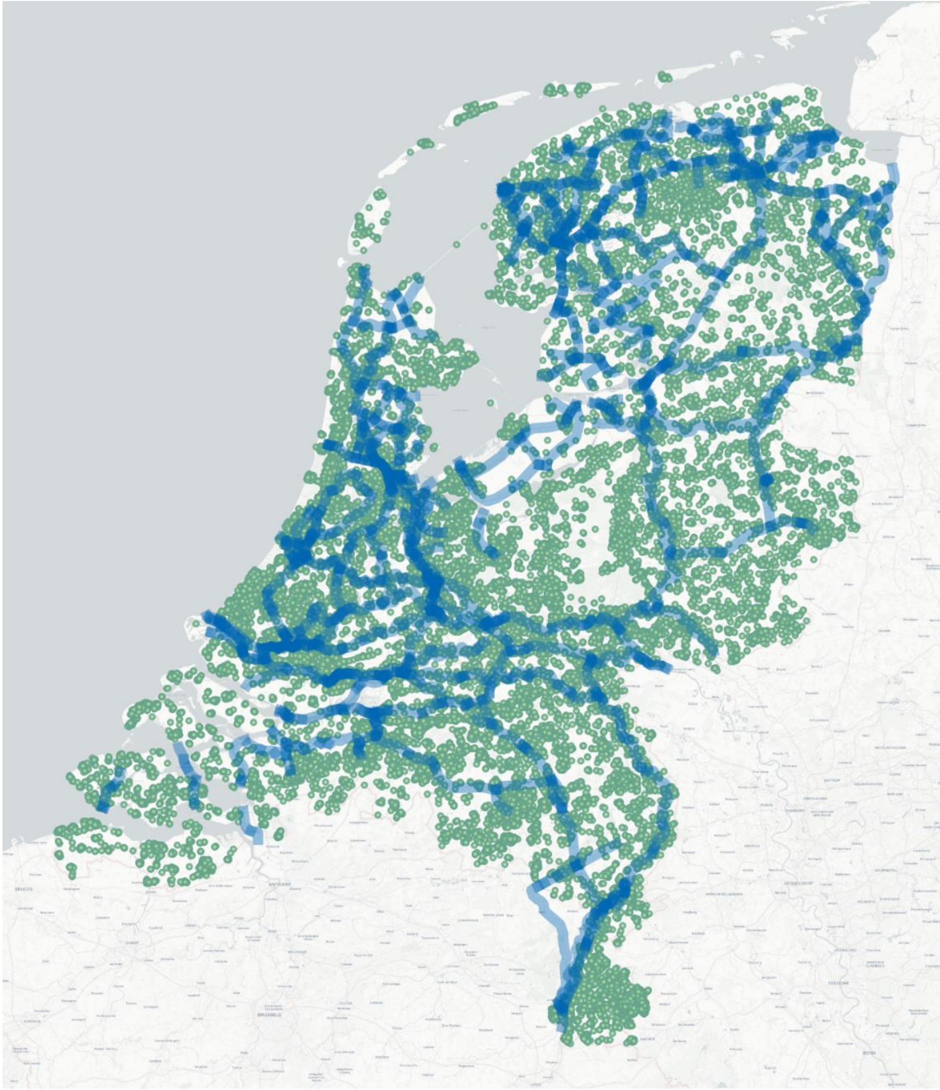
CHARACTERISTIC	DATA SOURCE
Geolocation	Basisregistratie Adressen en Gebouwen (BAG)
Building information (year built, size)	Basisregistratie Adressen en Gebouwen (BAG)
Building type	Kadaster

To determine the building type based on the BAG and the cadastral map, some preprocessing was done. The definitions of the building types are as follows:

- Apartment: a building with multiple residential objects
- Detached home: a building which does not touch any other building with a residential object
- Semi-detached home: a building which touches exactly one building with a residential object, which in turn only touches this building
- Corner home: a building which touches exactly one building with a residential object, which in turn touches more than one building with a residential object
- Terraced home: a building which touches more than one building with residential objects

The notional portfolio itself is generated in such a way that it is well diversified and spread out over the country. This is achieved by separating the country in postal code zones based on the first two numbers of the postal code. This results in a somewhat uniform distribution with regard to the number of houses in a zone. Then, addresses are picked at random until in each zone, the portfolio has a total rebuild value of about 15 billion euro. That notional portfolio is plotted in Figure 11, alongside the major rivers.

FIGURE 11: NOTIONAL PORTFOLIO FOR THE NETHERLANDS (GREEN DOTS), PLOTTED TOGETHER WITH THE MAJOR WATERWAYS (BLUE)



Data sources used: portfolio information as in Figure 10 and river locations as in section "Territory characteristics".

Rebuild value

The main costs that an insurer would incur in case of a river flood event would be the rebuild cost of the damaged buildings. To give a general overview of the value-at-risk, the rebuild value is calculated based on the building's surface area and, in some cases, the building type. Since the rebuild value can differ substantially between countries, a different approach is followed for each country in the sample.

In the Netherlands the association of insurers (Verbond van Verzekeraars) publishes a rebuild value meter for homes every year.[17] In this report, a simplified version of this monitor's 2024 version is used, which ignores the additions and discounts. Using this methodology, the rebuild value of insured homes in the Netherlands is a function of surface area and building type.

In France, reconstruction costs are not quoted directly. As a proxy for the cost of reconstruction, we will use a construction cost per square meter calculated by the Centre Scientifique et Technique du Bâtiment (CSTB).[18]

[17] Verbond van Verzekeraars (2024). Indexcijfer inboedels. Retrieved from https://www.verzekeraars.nl/branche/data-analytics-en-onderzoek/cijfers-statistieken/indexcijfers-inboedels-en-gebouwen.

[18] Centre Scientifique et Technique du Bâtiment. Règlementation Thermique des Bâtiments Existants. Retrieved from https://rt-re-batiment.developpement-durable.gouv.fr/IMG/pdf/_20230101_fa_calcul_de_la_valeur_d_un_batiment_v1_12.pdf.

In 2023, these costs amounted to 1,855 euros per square meter for housing. At this stage, this is a single proxy for the whole country, and does not take into account different geographical conditions. We could also extend this proxy by building type. The following data is required as input to calculate rebuild values for insured homes in France:

- Policy location (or address to geocode)
- Surface area of insured property
- Type of property insured (house/apartment)
- Floor of insured property

Risk characteristics

As mentioned in the Required Data section, risk characteristics data is necessary to accurately assess flood risk and losses. First, there are flood hazard characteristics: the flood depth, the flood duration and the probability of occurrence are key flood characteristics influencing the risk and losses. The second type of relevant variables are territory characteristics such as proximity to a river or coast, but also the relative elevation to water. In our flood risk and losses modelling, these granular data are required for each insured policy in the notional portfolio. The addition of this data to the address is integrated into the framework as detailed in the Detailed Approach section and Appendix B.

This section focuses on these two types of risk characteristics, as well as climate scenarios used for assessing impact of climate change on flood, and summarizes risk characteristics differences between the two implementations of the framework.

Differences between catastrophe tool and scenario analysis tool

Even though the general framework within the catastrophe tool and the scenario analysis tool is the same, some differences exist in the risk data that is used. These are summarized in the table below.

FIGURE 12: DIFFERENCES BETWEEN CATASTROPHE TOOL AND SCENARIO ANALYSIS TOOL

CHARACTERISTIC	CATASTROPHE TOOL	SCENARIO ANALYSIS TOOL
Flood depths	One-in-x-year events	Simulated from GCM/GHM combinations
Flood types	River, Sea	River
Climate change scenarios	No	Yes
Protection levels	Actual	Varying : [No, one-in-100, FLOPROS]
Horizon	As-is	2024-2060
Output and interpretation	Losses from an event of certain likelihood (one-in-x-year flood events)	Yearly losses corresponding to the maximum yearly flood event observed, within the scenario considered

The characteristics of the catastrophe tool make it a useful framework to evaluate catastrophe risk of a certain portfolio over a short horizon, for different probabilities of extreme events occurring. On the other hand, the scenario analysis tool is fit for scenario analysis, taking into account different scenarios of climate development, protection levels and a longer time horizon.

Another difference is that the catastrophe tool takes sea floods into account in addition to river floods, while the scenario analysis tool only incorporates river flood events. This means that the scenario analysis from the scenario analysis tool is less suitable for countries where sea flood is a major risk. Note that for the Netherlands, protection against sea flood is such that even for events with a one-in-100,000 return period the impact of sea flood events is limited; even though a large part of the country borders the sea and/or is below sea level. This can also be derived from the results of the catastrophe tool, which are shown in the Results section. The same can be said about France, where around 1.5 million people live in areas at risk of sea flooding, mainly in northern France. However, many defences have been built and the flood risk observatory, SHOM, has developed expertise to prevent and warn of high risk of sea flooding.[19] In the next sections we elaborate in detail on the data and assumptions used for risk characteristics in both tools.

[19] SHOM. Missions. Retrieved from https://www.shom.fr/en/node/15.

Flood hazard characteristics

The assessment of flood depth, flood duration, water flow speed, flooded area and flood return period enables risk and loss modelling. These are key characteristics which must be reliable, accurate and regularly updated. In this section, the flood hazard open data sources selected for this work are presented.

Flood hazard characteristics data selected for the catastrophe tool

In the European Union, including France, flood risk management is part of the European Directive 2007/60/EC of 23 October 2007 (known as the Floods Directive).[20] This directive aims to provide a framework for member states to reduce the negative consequences of flooding on human health, economic activity, environment and heritage.

In France, this directive is implemented in three distinct steps for each river basin: 14 rivers basins in France, including overseas departments. Those basins include, for example, the Rhône-Mediterranean basin and the Seine-Normandie basin:[21]

- Preliminary risk assessment where census of historical events and production of indicators characterizing the issues at stake, particularly with regard to exposed populations are carried out resulting in selection of areas at major risk of flooding
- Mapping of flood-prone and flood risk over the selected areas at major risk of flooding
- Local flood risk management strategy where local measures are detailed to reduce the vulnerability of areas, to prevent and protect against floods

In this study, the focus is on preliminary risk assessment and flood risk over selected areas at major risk of flooding to provide information on flood depth, flooded area and flood return period over 124 areas at major risk of flooding throughout France.

These areas are home to major issues (population, jobs, buildings, etc.) that are likely to be affected by flooding. The maps of the flood risk over at-risk territories represent the areas that are subject to flooding and the water heights that can be reached during river flooding or marine submersions. These 'at-risk territories' are defined by prefecture with the preliminary risk assessment where in-depth risk assessment is done by French experts (geographers, hydrologists, cartographers) studying historical floods, area topography and protective elements. Once the at-risk territories identified, experts estimate flood depth and flood return period associated with the areas.

However, the preliminary risk assessment might be incomplete, and some risky areas with a 'issues at stake indicator' below the defined threshold might be excluded. Thus, certain risky areas might be absent, and the data from this directive provides a broad view of risk but with some gaps. Nevertheless, the mapping is updated every six to eight years to complete potential missing areas and incorporate changes in risk evaluation due to risk mitigation actions, housing development or territorial changes.

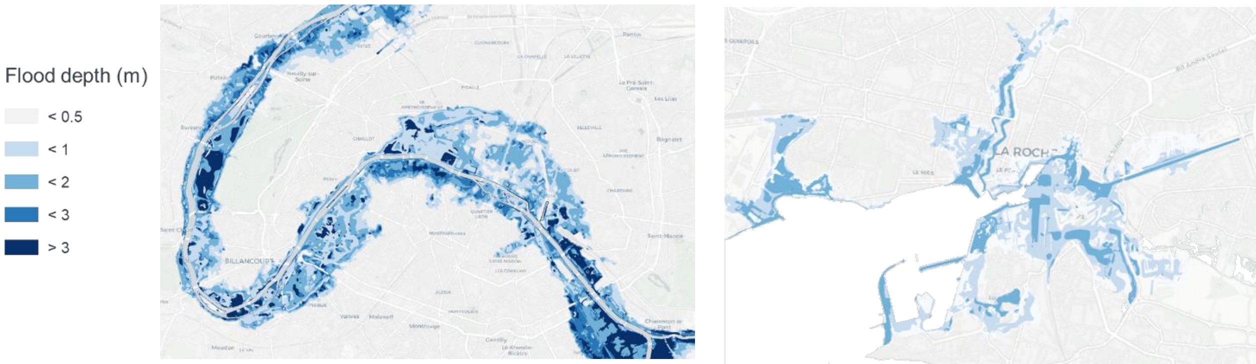
These flood hazard open data describe two kinds of floods, river overflow and marine submersion, for three return periods: 20 years (high probability), 200 years (medium probability), and 1,000 years (low probability).[22] In addition, flood depth and at-risk area are available for the 200-year return period according to the IPCC's RCP 8.5 scenario (see the section on flood hazard data for the scenario analysis tool) by 2100 for marine submersion.

[20] EUR-Lex. Directive 2007/60/CE du Parlement Européen et du Conseil du 23 octobre 2007 relative à l'évaluation et à la gestion des risques d'inondation. Retrieved from https://eur-lex.europa.eu/legal-content/FR/TXT/?uri=celex%3A32007L0060.

[21] Prèfet de la Charante-Maritime. Bassins hydrographiques de France. Retrieved from https://www.charente-maritime.gouv.fr/Actions-de-l-Etat/Environnement-risques-naturels-et-technologiques/Eau-et-milieux-aquatiques/Directives-europeennes-SDAGE-PAOT-SAGE/Directive-cadre-sur-l-eau-DCE/Bassins-hydrographiques-de-France.

[22] The high probability event is associated with a 10- to 30-years return period, the medium probability to a 100- to 300-years return period and the low probability event to a 1,000-years or more return period.

FIGURE 13: RIVER FLOODING FOR 1,000-YEARS RETURN PERIOD FOCUS ON PARIS | SEA FLOODING FOR 1,000-YEARS RETURN PERIOD FOCUS ON LA ROCHELLE



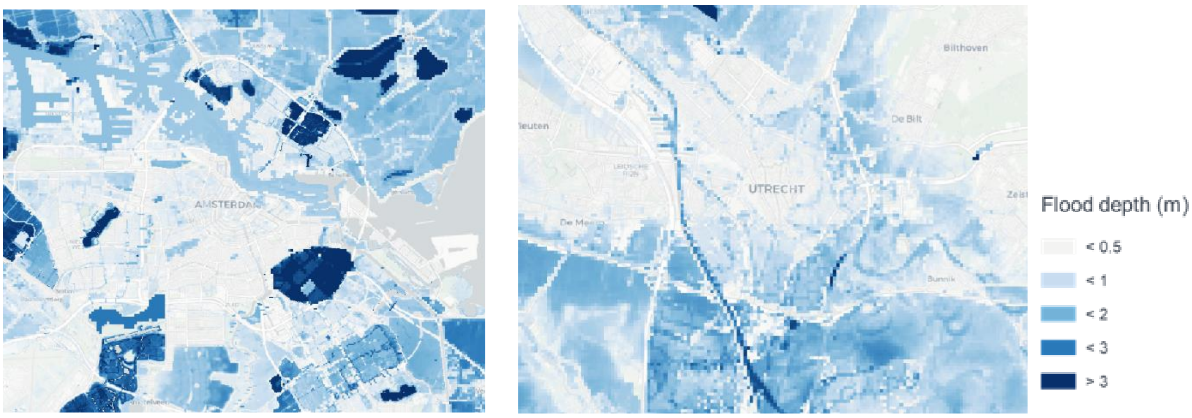
Data sources used: portfolio information as in section "Portfolio composition – France" and flood hazard data as outlined in this section.

It should be noted that water flow speed is also provided on several at-risk areas, but the information is not consistent for all the areas. Thus, water flow speed is not taken into account in this study. To perfectly assess flood risk and loss, flood duration and speed of water flow are missing flood hazard data.

For the Netherlands, the results are based on the flood depth maps which were developed as part of the nationwide information system water and floods (Landelijk Informatiesysteem Water en Overstromingen [LIWO]). These maps consider potential flood depths for four different return periods (one in 10 years, one in 100 years, one in 1,000 years and one in 100,000 years), given the current state of the climate. These maps incorporate two types of floods, fluvial and coastal. Other event types such as pluvial floods are not included.

Note that in Appendix A, the explanatory power of several geographic characteristics on the flood hazard data for the catastrophe tool is analysed.

FIGURE 14: RIVER FLOODING FOR 1,000-YEARS RETURN PERIOD FOCUS ON AMSTERDAM AND UTRECHT



Data sources used: portfolio information as in section "Portfolio composition – the Netherlands" and flood hazard data as outlined above.

Flood hazard characteristics data selected for the scenario analysis tool

The aim of the scenario analysis tool is to analyse river-based flood risk for an insurance portfolio. Therefore, flood modelling itself is not in the scope of this report. Instead, open data is used to determine the potential flood depths.

When considering future river-based flood risks, some of the main drivers are the expected precipitation and the expected snow melt. Both of these factors are highly influenced by climate change, which is expected to cause more extreme weather events, including high precipitation events.[23] However, to what extent this will be the case is still dependent on human actions, and thus clouded in uncertainty.

[23] Tabari, H. (August 2020). Climate change impact on flood and extreme precipitation increases with water availability. Nature Portfolio. Retrieved from https://www.nature.com/articles/s41598-020-70816-2.

For their 2014 Assessment Report (AR5).[24] the Intergovernmental Panel on Climate Change (IPCC) defined climate change scenarios based on the concentration of greenhouse gases, which are called representative concentration pathways (RCPs). In this report, three of these RCPs are considered:

- RCP 2.6: This pathway is described as 'very stringent' and would likely limit the global temperature rise to 2°C by 2100
- RCP 6.0: In this intermediate scenario, the greenhouse gas emissions would peak around 2080 and then start to decline
- RCP 8.5: In the final scenario a 'business as usual' situation is assumed, in which little effort is made to collectively reduce the emissions of greenhouse gases

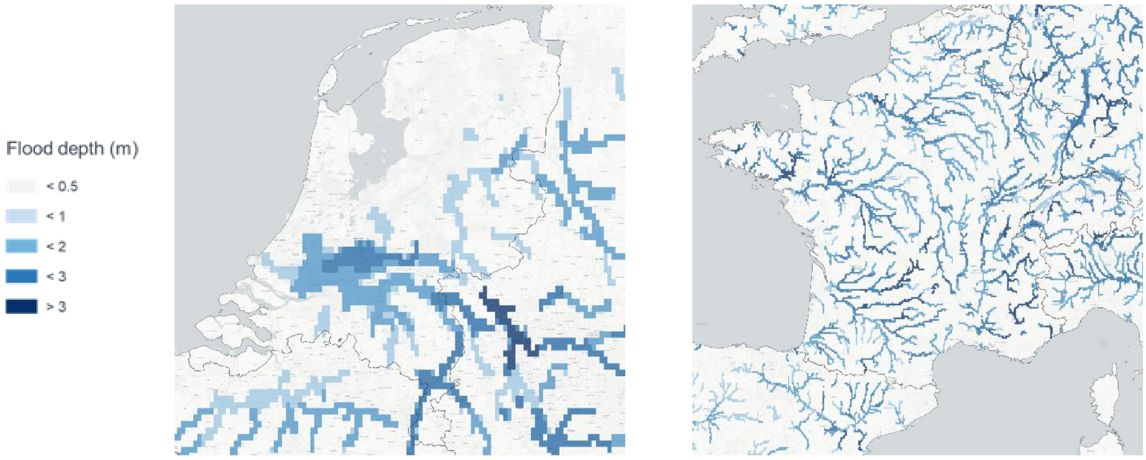
Modelling the impact of climate change is a difficult endeavour; however, there are several institutions which have tried to do so. Each of these have developed their own model, each with its own distinct benefits and drawbacks. The Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) compares these models by running them on a uniform dataset. This report uses the outcomes of the ISIMIP2b scenarios for all available climate and impact models, which are:

- Climate models: GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC5
- Impact models: CLM4.5, CWATM, H08, LPJmL, MATSIRO, WaterGAP2

The outputs of those impact models are then fed into CaMa-Flood, which is a global hydrodynamic model, and used to calculate flood events given set protection levels. The resulting output consists of a map of maximum yearly flood depths at a resolution of 150 arcsec for the period from 2006 to 2100.[25]

To keep this report concise, only one of the climate models mentioned before is considered, namely the IPSL-CM5A-LR. This model is also considered by the ISIMIP to be the model with the highest priority.[26] To further aggregate the results, the mean of the impact models is taken when considering the losses.

FIGURE 15: A SAMPLE OF FLOOD DEPTHS ACCORDING TO THE IPSL-CM5A-LR CLIMATE MODEL IN COMBINATION WITH THE CLM 4.5 IMPACT MODEL, WITHOUT PROTECTION FOR THE RCP 8.5 SCENARIO IN THE YEAR 2030



Legend **Flood depths for the Netherlands** **Flood depths for France**

Territory characteristics

The understanding of topography and geography of a territory is a key step in flood modelling. The closer the dwelling is to the water (river or sea), the higher the risk is. Moreover, if the dwelling is below or at the same level as the water (river or sea), the risk is greatly enhanced. Contrarily, the higher the house is above the water level, the less at risk it will be.

[24] Intergovernmental Panel on Climate Change. AR5 Synthesis Report: Climate Change 2014. Retrieved from https://www.ipcc.ch/report/ar5/syr/.

[25] Willner, Sven. Flood Processing. Zenodo. Retrieved from https://doi.org/10.5281/zenodo.1241051.

[26] Inter-Sectoral Impact Model Intercomparison Project (January 2021). ISIMIP2b Simulation Protocol. Retrieved from https://www.isimip.org/documents/553/ISIMIP2b_protocol_210131_noEnergy_IV_JS-1_IV_general.pdf.

To heed these considerations in modelling and analyses, the following data sources are selected:

FIGURE 16: TERRITORY CHARACTERISTICS DATA SOURCES

CHARACTERISTIC	FRANCE	THE NETHERLANDS
River location	French Mapping Agency (IGN)	Informatiemodel Water (IMW)
Coastline locations	French Mapping Agency (IGN)	Kaderrichtlijn Mariene Strategie (KMR) Mariene wateren Nederland
Elevation (DEM)	French Mapping Agency (IGN)	Actuele Hoogtebestand Nederland

As mentioned in the previous section, the flood risk data (for the scenario analysis tool) obtained from the ISIMIP project is at a resolution of 150 arcsec. This resolution, which in the Netherlands (at 52° latitude) translates to about 2.85 x 4.63 km or about 13.20km^2, is suitable for many analytical purposes. However, when considering individual buildings and addresses, as this report does, this resolution is not sufficient.

Therefore, for the Netherlands a relative elevation is used to further upsample the flood risk maps, using a terrain filter.[27] This terrain filter is employed using the high-resolution digital elevation map (DEM) described in Figure 16 at a resolution of 1x1 meters. The aim is to upsample the flood depth map to 10x10 meters; therefore the DEM is downsampled to this resolution using bilinear interpolation before applying the terrain filter.

Protection levels

Another characteristic influencing flood risk and loss is the measures taken by governments against river flooding such as dike improvements or the creation of larger floodplains. In recent years many European governments have implemented programs to increase protection against river floods.

Examples include the Ruimte voor de Rivieren and Maas works projects in the Netherlands, which provide more space for rivers and allow for higher discharges without leading to floods.[28]

To include the uncertainty in flood protection in the future scenarios for the scenario analysis tool, three protection levels are considered in this report:

- No protection
- Protection against events with a return period smaller than 100 years
- Protection measures in line with the global FLOod PROtection Standards (FLOPROS) database, which are norm protection levels as indicated by local governments[29]

In the ISIMIP data, the likelihood of a flood event is calculated by comparing it to historical data using a generalized extreme value distribution, as discussed by Sauer et al. in their 2021 paper.[30]

For the catastrophe tool, the actual status of flood prevention and protection systems are incorporated. For the Netherlands these are provided by Rijkswaterstaat.[31] In France, these are provided in the flood hazard database which is updated every six to eight years (data used for this study have been updated in 2020), and therefore takes into account updates to the protection systems that have been put in place over time. This dataset corresponds to the high flood probability area (Territoires à Risques Importants d'Inondation [TRI]). The data has been compiled in accordance with the Flood Directive standard.[32]

[27] Bryant, S., Schumann, G, Apel, H, Kriebich, H. & Merz, B. (February 2024). Technical note: Resolution enhancement of flood inundation grids. European Geosciences Union. https://hess.copernicus.org/articles/28/575/2024/hess-28-575-2024.html.

[28] Rijkswaterstaat. Ruimte voor de rivieren. Retrieved from https://www.rijkswaterstaat.nl/water/waterbeheer/bescherming-tegen-het-water/maatregelen-om-overstromingen-te-voorkomen/ruimte-voor-de-rivieren.

[29] Scussolini, P., Aerts, J.C.J.H., Jongman, B., Bouwer, L.M., Winsemius, H.C., De Moel, H. & Ward, P.J. (2016). FLOPROS: An evolving global database of flood protection standards.Vrije Universiteit Amsterdam. Retrieved from https://research.vu.nl/en/publications/flopros-an-evolving-global-database-of-flood-protection-standards.

[30] Sauer, I.J., Reese, R., Otto, C., Geiger, T, et al. (April 2021). Climate signals in river flood damages emerge under sound regional disaggregation. Nature Portfolio. Retrieved from https://www.nature.com/articles/s41467-021-22153-9.

[31] Rijkswaterstaat. Overstromingskansen actueel (2022). Retrieved from https://basisinformatie-overstromingen.nl/#/viewer/18.

[32] Official Journal of the European Union (October 2007). Directive 2007/60/EC of the European Parliament and of the Council of 23 October 2007 on the assessment and management of flood risks. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32007L0060

LOSS FUNCTION

Given the portfolio variables and risk characteristics, a loss function needs to be applied to determine losses per insured object in case of a flood event. A depth-damage function is required to translate flood depths to percentage losses of total rebuild value.

The loss function is as follows for a single flood event and a single insured home:

$$Loss = \begin{cases} 0 & \text{if the home is an apartment} \\ Damage\ function(flood\ depth) * Rebuild\ value & \text{all other types of homes} \end{cases}$$

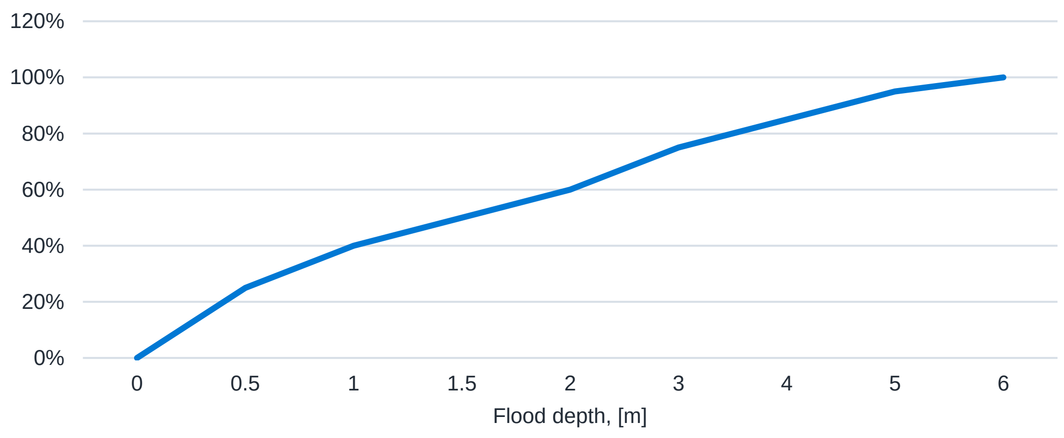
Here, the damage function denotes the percentage of value of the insured home that is damaged, which is dependent on the flood depth corresponding to the flood event. In this calculation, two assumptions are made to streamline and simplify the calculation. First, all homes are assumed to be on street level, which is not uncommon in Europe. Furthermore, apartments are assumed to be elevated, and therefore have zero loss. Those assumptions were made because the available data did not allow us to go into more detail.

This general approach is independent of the data that is used; however, details of the implementation can depend on the actual data that is available. Note, for instance, that the loss function chosen here is relatively simple: It considers only the variables which were reliably available in open data sources for this study. When evaluating an actual portfolio with more information available, the loss function could be made more sophisticated by, for example, adding floor heights or type of building material. Additionally, the assumption that the loss is proportional to the rebuild value could be tested by comparing them to actual claims.

Depth-damage function

The amount of damage a flood event causes to a building depends on several factors, most notably the building type and the flood depth. A flood depth-damage function maps these drivers to a damage factor. This study uses the JRC's global depth-damage function,[33] which aims to be a single, globally applicable, set of depth-damage functions, with separate functions for each continent and for different types of real estate. This analysis employs the damage function for residential buildings in Europe.

FIGURE 17: THE JRC'S DEPTH-DAMAGE FUNCTION FOR EUROPEAN RESIDENTIAL BUILDING[34]



[33] Huinziga, J. & De Moel, H. (April 2017). Global flood depth-damage functions: Methodology and the database with guidelines. European Commission, JRC Publications Repository. Retrieve from https://publications.jrc.ec.europa.eu/repository/handle/JRC105688.

[34] Huinziga, J. & De Moel, H. (April 2017). Global flood depth-damage functions: Methodology and the database with guidelines. European Commission, JRC Publications Repository. Retrieve from https://publications.jrc.ec.europa.eu/repository/handle/JRC105688.

Results and comparison

In this section we present the results of the flood risk analyses that have been performed in the catastrophe tool and the scenario analysis tool, for the countries France and the Netherlands. Furthermore, we highlight and explain the differences that can be observed.

FRANCE

This section shows the results of the scenario analysis tool and the catastrophe tool for France, as well as the processing time of the catastrophe tool model on the French notional portfolio.

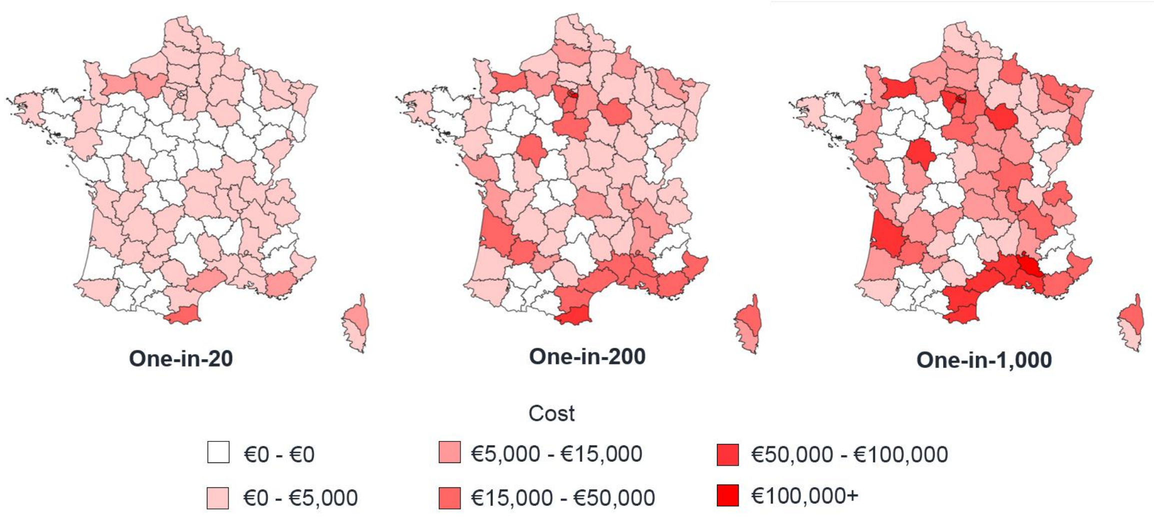
Based on the analysis conducted, the processing time for the catastrophe tool model is approximately proportional to the number of policies entered, as shown in Figure 18. This relationship underlines the scalability of the tool and its ability to handle large portfolios efficiently.

FIGURE 18: PROCESSING TIME (S) FOR CATASTROPHE TOOL MODEL ACCORDING TO NUMBER OF POLICIES IN INPUT

NUMBER OF POLICIES	PROCESSING TIME (S)
10k	8.75
100k	21.3
1M	107.2

Figure 19 shows the average losses (total loss divided by number of households) by department for the French portfolio using the catastrophe tool. The results shows that, as expected, the losses are higher for more severe scenarios. Also, departments with major rivers such as the Garonne, Rhone or Seine or on the seafront have higher average costs. Furthermore, the results of this model show that certain departments are more spared from the risk of flooding than others, particularly in the west and mountainous regions (Pyrenees and Alps). This can be explained by the fact that flash flooding is out of scope of this model.

FIGURE 19: AVERAGE COST BY DEPARTMENT IN FRANCE FOR RIVER AND SEA FLOOD USING CATASTROPHE TOOL:



Data sources used: portfolio information as in section “Portfolio composition – France”, flood hazard data as in section “Flood hazard characteristics data selected for catastrophe tool”

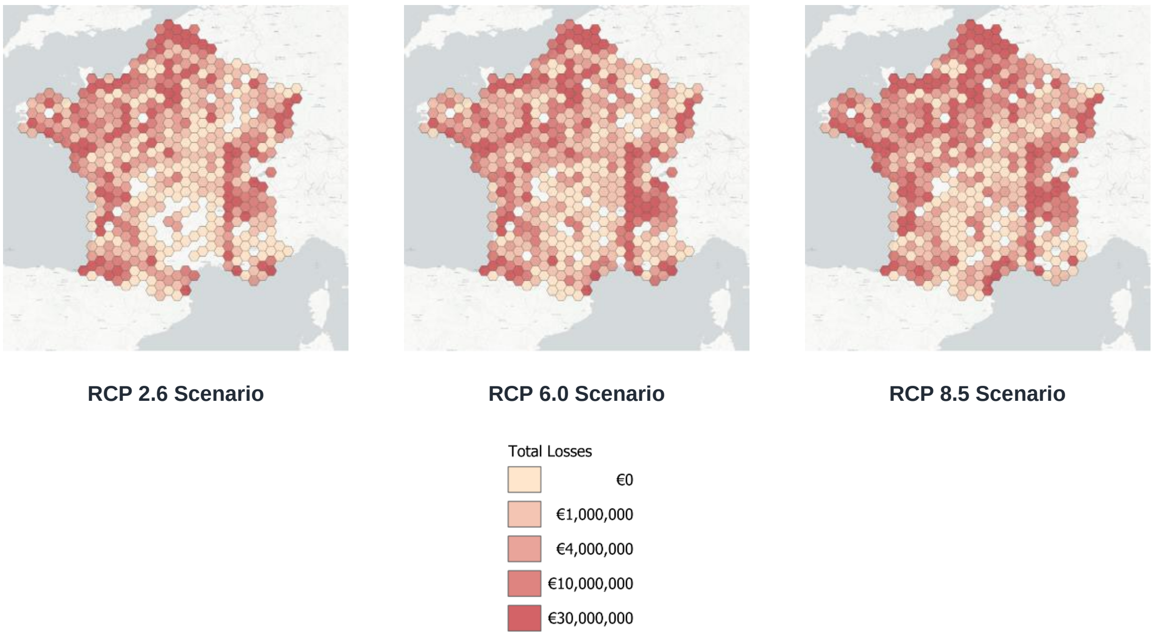
In Figure 20 the losses per return period are tabulated, including a percentage of total insured amount that the losses relate to. For flood events with a return period of one in 1,000 years, the losses correspond to approximately 5% of the total insured value of the portfolio. The numbers indicate a significant level of risk exposure, highlighting the importance of robust risk management strategies to mitigate the potential financial impact.

FIGURE 20: LOSSES FOR FRENCH PORTFOLIO – CATASTROPHE TOOL

RETURN PERIOD	LOSS	PER EUR 1,000 INSURED AMOUNT
1-in-20	EUR 165 mln	3.2
1-in-200	EUR 1,067 mln	20.9
1-in-1,000	EUR 2,445 mln	47.9

Figure 21 shows the total losses for the French portfolio over the period 2024-2060, as projected by the scenario analysis tool. Note that in total, higher flood depths and higher losses are observed in the more extreme scenarios. However, the floods can occur in different places under different scenarios—for instance, due to higher precipitation events occurring upstream of locations which are in basis more prone to flooding, which means that the losses are not necessarily higher in each grid for the more extreme scenarios.

FIGURE 21: TOTAL LOSSES IN THE FRENCH PORTFOLIO PER RCP SCENARIO OVER PERIOD 2024-2060 (IN HEXAGONS OF 50X50 KM), ONE-IN-100 PROTECTION USING SCENARIO ANALYSIS TOOL (RCP 2.6 SCENARIO)



Data sources used: portfolio information as in section “Portfolio composition – France”, flood hazard data as in section “Flood hazard characteristics data selected for scenario analysis tool”

In Figure 22 the annualized losses per scenario are tabulated for one-in-100 protection levels and FLOPROS protection. In the most severe scenario calculated, the losses can amount to 0.5% of the portfolio, almost tripling the losses of the least severe scenario. These results furthermore show higher losses under FLOPROS protection than under one-in-100 protection, implying that average protection under FLOPROS is lower than one in 100.

FIGURE 22: ANNUALIZED LOSSES FOR FRENCH PORTFOLIO OVER PERIOD 2024-2060 – SCENARIO ANALYSIS TOOL

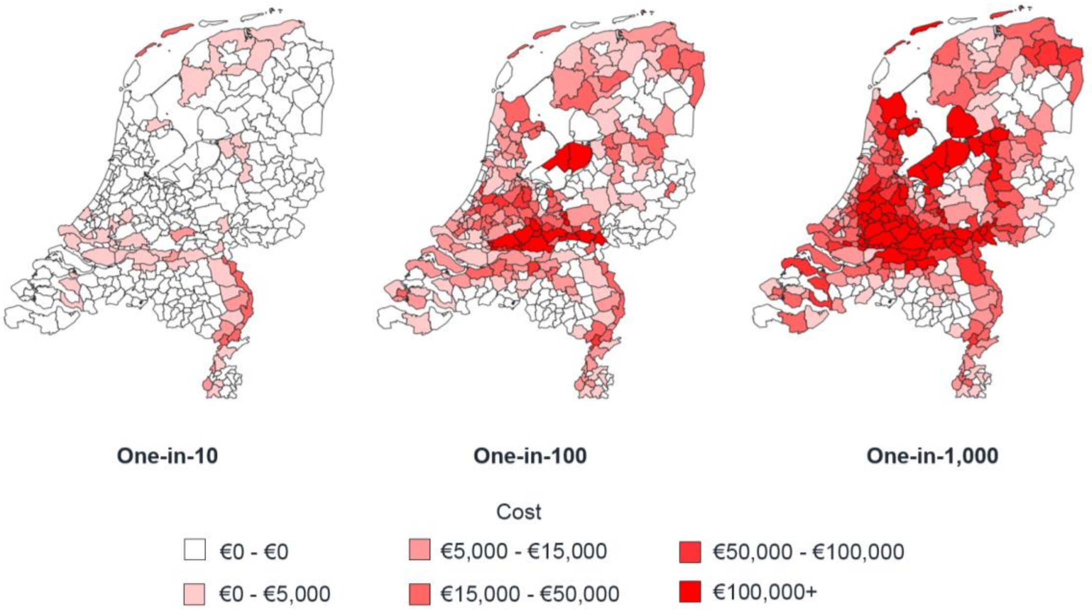
	PROTECTION ONE-IN-100		FLOPROS PROTECTION	
RCP SCENARIO	ANNUALIZED LOSS	PER EUR 1,000 INSURED AMOUNT	ANNUALIZED LOSS	PER EUR 1,000 INSURED AMOUNT
RCP2.6	EUR 77 mln	1.5	EUR 94 mln	1.8
RCP6.0	EUR 152 mln	3.0	EUR 188 mln	3.7
RCP8.5	EUR 192 mln	3.8	EUR 236 mln	4.6

These findings highlight the importance of using advanced tools such as the catastrophe tool and scenario analysis tool to manage risk and plan for future contingencies. They provide valuable insights that can guide decision-making processes and ensure that strategies are data-driven and aligned with the potential risks and challenges of the future.

THE NETHERLANDS

In Figure 23, the average cost by municipality in the Netherlands for river and sea flood is shown, under different likelihood of events. These results are based on the catastrophe tool. It can be seen that the events with high probability are largely situated around the lowlands close to the rivers Maas and Waal in the south of the country, in Flevoland near the IJsselmeer and around the Waddenzee in the north. For the more extreme events with lower likelihood of occurrence, flood losses can be observed throughout almost the entire country, the exceptions being the mid-south region around Eindhoven and the (north-)eastern regions of the Achterhoek, Twente and Drenthe.

FIGURE 23: AVERAGE COST BY MUNICIPALITY IN THE NETHERLANDS FOR RIVER AND SEA FLOOD USING CATASTROPHE TOOL



Data sources used: portfolio information as in section “Portfolio composition – the Netherlands”, flood hazard data as in section “Flood hazard characteristics data selected for catastrophe tool”

In Figure 24 the total insured losses for the Dutch portfolio in the catastrophe tool are shown for various return periods of flood events. These are obtained for the Dutch notional portfolio of home insurances and incorporate the current state of climate variables and actual protection levels. Note that there are unmodelled losses in the dataset, such as those caused by pluvial floods.

FIGURE 24: LOSSES FOR DUTCH PORTFOLIO BY RETURN PERIOD – CATASTROPHE TOOL

RETURN PERIOD	INSURED LOSS	PER EUR 1,000 INSURED AMOUNT
1-in-10	EUR 36 mln	2.4
1-in-100	EUR 826 mln	55.1
1-in-1,000	EUR 2,352 mln	156.8
1-in-100,000	EUR 3,607 mln	240.5

The results from the catastrophe tool show that on average once every 10 years, a loss equal to EUR 2.4 per EUR 1,000 insured amount of the portfolio can be expected. On a horizon of 100 years, a loss equal to EUR 55.1 per EUR 1,000 insured amount is, on average, expected once. This number increases to EUR 240 per 1,000 (almost 25%) on average once every 100,000 years. Note that these numbers are fully based on the current state of the climate, while the scenario analysis tool can take climate change into account.

To this end, Figure 25 shows the annualized flood losses for the Dutch portfolio in the scenario analysis tool. These span the period 2024-2060, vary by RCP scenario and include protection up to one-in-100-year return period events. Please note that these results are not comparable to the losses estimated by the catastrophe tool, given that the latter are results if a one-in-x-year event was to occur, whereas the former shows an annualized loss. Estimating an annualized loss based on the results of the catastrophe tool is outside the scope of this paper.

FIGURE 25: ANNUALIZED LOSSES FOR DUTCH PORTFOLIO OVER PERIOD 2024-2060, ONE-IN-100 PROTECTION – SCENARIO ANALYSIS TOOL

RCP SCENARIO	ANNUALIZED LOSS	PER EUR 1,000 INSURED AMOUNT
RCP2.6	EUR 32 mln	2.1
RCP6.0	EUR 75 mln	5.0
RCP8.5	EUR 187 mln	12.4

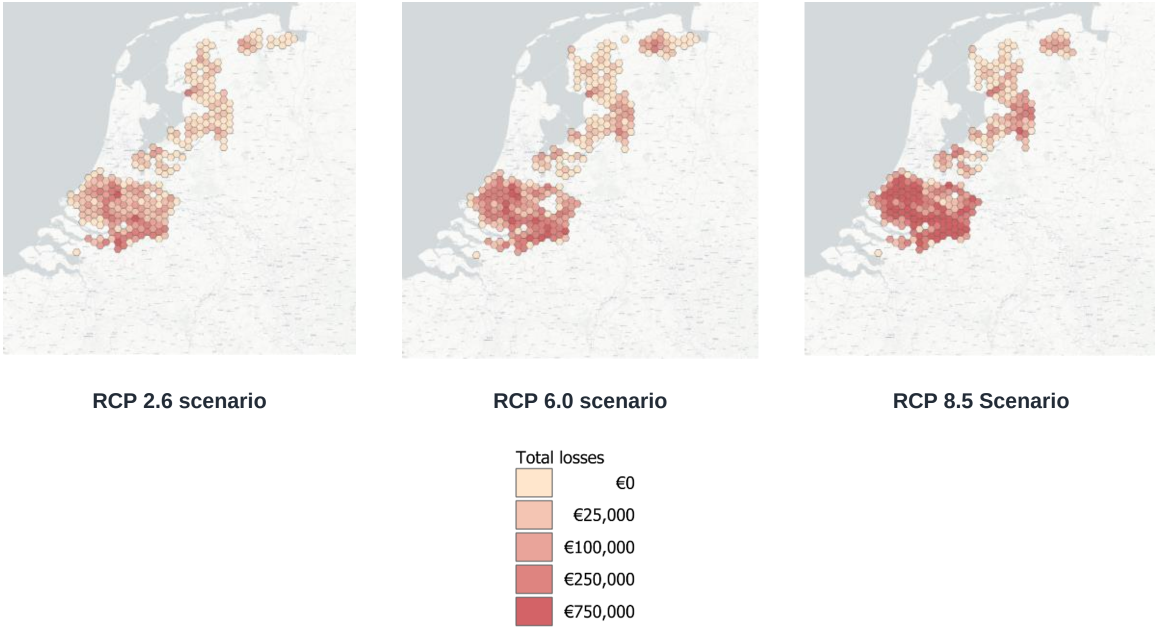
From this figure we observe that even in the most lenient climate scenario considered (RCP2.6), the annualized losses in the portfolio are substantial: EUR 32 million, which is EUR 2.1 per EUR 1,000 insured amount. When the RCP6.0 scenario is processed, the annualized insured losses more than double to EUR 75 million (EUR 5 per 1,000 of total portfolio). Going to the most extreme scenario considered, RCP8.5, the losses again more than double and amount to EUR 187 million (EUR 12 per 1,000).

Note that the numbers above assume protection against river floods with a one-in-100-year return period. The losses will be much larger in case no protection is assumed. More interestingly, when protection levels are assumed to correspond to the FLOPROS database, zero losses are observed. This means that in the simulation runs of the models, no flood events occurred in the Netherlands with return period large enough to exceed the protection levels. In other words, if protection levels against river floods in the Netherlands align with the standards set by local authorities, as incorporated in the FLOPROS database (which range from one in 250 to one in 10,000 years, depending on the region), no flood events would occur before the year 2060 in the scenario set that is considered.

The latter observation contrasts with the insured losses which observed in the catastrophe tool, where insured losses are already observed for flood events with a one-in-10-year return period using current climate variables and actual protection levels. Also, the losses with a one-in-100-year return period in the catastrophe tool are much higher than the losses in the scenario analysis tool for all RCP scenarios considered.

This suggests that either the flood events following from the current climate are more severe than flood events following from the various climate scenarios we use, or that the actual protection levels against flood events are considerably lower than the levels set in the FLOPROS database. Given that we see more extreme flood events occurring with more extreme climate scenarios, the latter explanation is more likely.

FIGURE 26: TOTAL LOSSES IN THE DUTCH PORTFOLIO PER RCP SCENARIO OVER PERIOD 2024-2060 (IN HEXAGONS OF 10X10 KM), ONE-IN-100 PROTECTION USING SCENARIO ANALYSIS TOOL



Data sources used: portfolio information as in section “Portfolio composition – the Netherlands”, flood hazard data as in section “Flood hazard characteristics data selected for scenario analysis tool”

The maps in Figure 26 show the total losses in the Dutch notional portfolio over the period 2024-2060 per RCP scenario considered. From the graphs it can be observed that the regions affected by floods do not vary much between the different climate scenarios. As for the French portfolio, the losses in a specific region are not necessarily higher under more extreme scenarios. However, the total losses resulting from the floods observed are more extreme for the higher RCP scenarios. This aligns with the general expectation that global warming increases the risk of river floods—for instance due to more and heavier extreme precipitation events.

COMPARISON

When comparing the results of the different tools for France and the Netherlands, it can be seen that in both countries increasingly heavy flood events and increasingly heavy climate scenarios lead to higher flood losses.

The increase of losses is, however, much steeper for the Netherlands than for France, which can likely be explained by a combination of a relatively larger concentration of waterways, more dense population of the country and higher protection levels. The first two observations yield a relatively larger exposure-at-risk. The latter observation causes a sharp increase of losses once catastrophic events beyond the level of protection are observed, which corresponds for many major Dutch waterways approximately to one-in-1,000-year events.

Key takeaways

In this report we have laid out a framework for estimating home insurance losses from damages to dwellings following flood events, based on open data. The framework builds on input data regarding portfolio information, climate information and protection levels. Two types of tools have been implemented. The first tool (catastrophe tool) provides insight into catastrophe risk by establishing the impacts of flood events with different return periods and making use of current climate and protection levels. The second tool (scenario analysis tool) can be used for scenario analysis, and gives insight into the impact of varying climate scenarios and protection levels over a longer time horizon. As both tools leverage open data sources, they are cost-effective alternatives for commercially available catastrophe models or scenario tools. Both approaches can be used in risk assessments for, e.g., the Solvency II ORSA, but can also serve as a basis to further develop pricing or risk models.

Both tools have been applied to notional portfolios of insurers in France and the Netherlands. The results show that, as expected, extreme flood events will affect a very large proportion of residential homes in these countries. When including the impact of varying climate scenarios, in scenarios with continued high GHG emissions the expected losses are higher than in a scenario where GHG emissions are reduced extensively. Furthermore, the level of flood protection assumed drastically impacts the losses as well.

The framework and the tools used for this study can be applied to real-life insurance portfolios in any European country, or even in other global regions. Also, the results of the analysis can be relevant for other parties, such as banks, municipalities or other government agencies.

The analysis furthermore shows that the extent to which results change in different scenarios can vary across the countries considered. Hence, local expertise is paramount in interpreting the outcomes.

Additional research

To read more research by Milliman professionals on climate change and catastrophe risks, please see the following articles, or visit the Milliman Climate Resilience Initiative:

- Extreme weather events in Europe
  https://www.milliman.com/en/extreme-weather-events-in-europe
- Milliman Climate Change Reporting Barometer
  https://www.milliman.com/en/insight/milliman-climate-change-reporting-barometer
- Developing climate risk scenarios for Solvency II ORSA
  https://www.milliman.com/en/insight/developing-climate-risk-scenarios-for-solvency-ii-orsa
- Causal modelling: A possible application considering climate risk and asset returns
  https://uk.milliman.com/en-gb/insight/causal-modelling-climate-risk-asset-returns
- Trial by wildfire: Will efforts to fix home insurance in California stand the test of time?
  https://us.milliman.com/en/insight/Trial-by-wildfire-Will-efforts-to-fix-home-insurance-in-California-stand-the-test-of-time
- Drought 2022 — Analysis of subsidence risk in France
  https://www.milliman.com/en/insight/secheresse-2022-analyse-du-risque-subsidence-en-france
- 10 ans de feux de forêt en France métropolitaine
  https://fr.milliman.com/fr-fr/insight/10-ans-de-feux-de-foret-en-france-metropolitaine

Appendices

Appendix A – Results analysis

In this appendix we plot results of the catastrophe tool based on different territory characteristics for France and the Netherlands.

FRANCE

Figure 27 shows that when insured buildings are very close to the river (distance <50 m), the observed percentage of addresses in the notional portfolio which is affected is more than 7%. This ratio decreases rapidly with higher distance to river, reaching a plateau of around 5% between 200 m and 1250 m. From this distance onwards, the percentage of affected addresses decreases more rapidly, reaching a new plateau of 3%, which seems constant up to 2 km from the river. So this variable does not seem to be the most discriminating. On the other hand, the same graph for distance from the coast (Figure 28) shows a decreasing linear relationship between claims rate and distance from the coast. Moreover, the claims rate for houses close to water is much higher in the case of marine submersion than in the case of river overflow: Floods caused by river overflows and those caused by marine submersion do not affect homes in the same way.

FIGURE 27 DISTRIBUTION OF NUMBER OF POLICIES AND CLAIMS FREQUENCY BY DISTANCE TO RIVER – FROM CATASTROPHE TOOL, ASSUMING EVENTS WITH SMALL PROBABILITY (ONE-IN-1,000-YEAR)

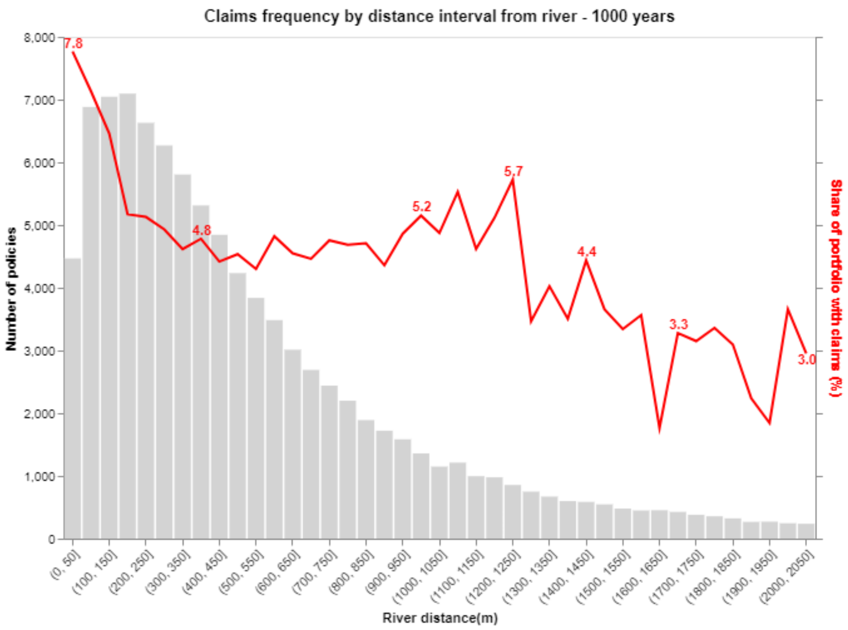
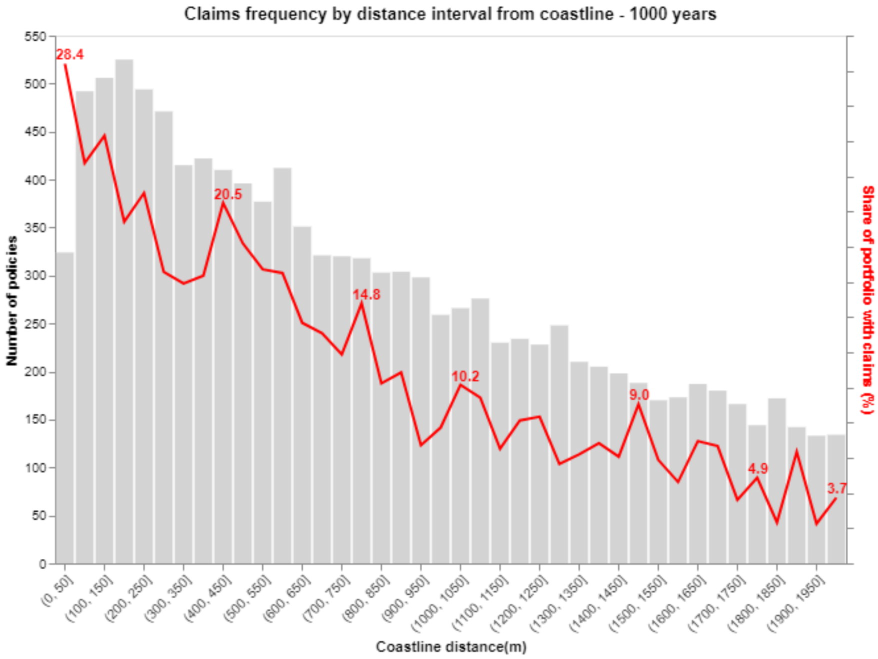


FIGURE 28 DISTRIBUTION OF NUMBER OF POLICIES AND CLAIMS FREQUENCY BY DISTANCE TO COASTLINE – FROM CATASTROPHE TOOL, ASSUMING EVENTS WITH SMALL PROBABILITY (ONE-IN-1,000-YEAR)



Relative elevation to river or sea level shows to be a more explanatory indicator of claims. In fact, as shown in Figure 29 and Figure 30, claim rates are highest when relative elevation is negative, and become very low when this quantity becomes positive again, or even zero when it exceeds 24 m.

FIGURE 29 DISTRIBUTION OF NUMBER OF POLICIES AND CLAIMS FREQUENCY BY RELATIVE ELEVATION TO COASTLINE – FROM CATASTROPHE TOOL, ASSUMING EVENTS WITH SMALL PROBABILITY (ONE-IN-1,000-YEAR)

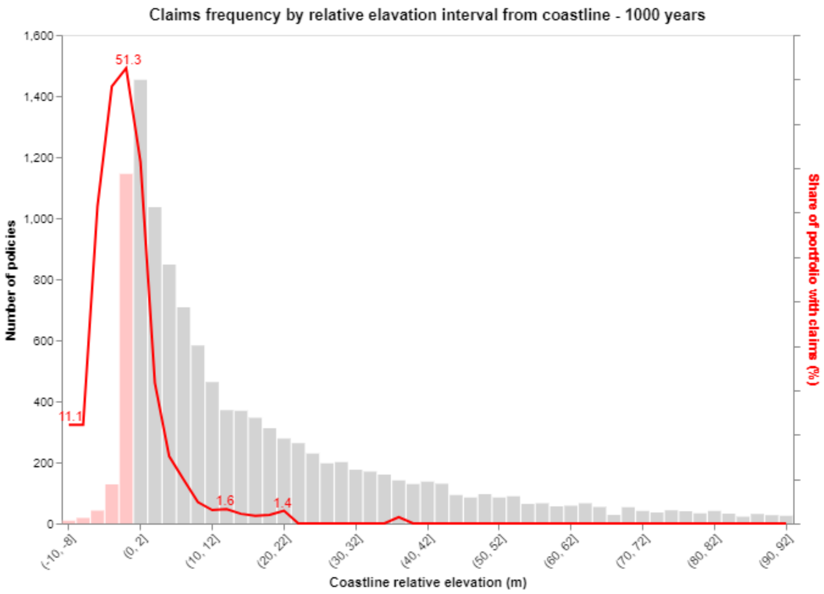
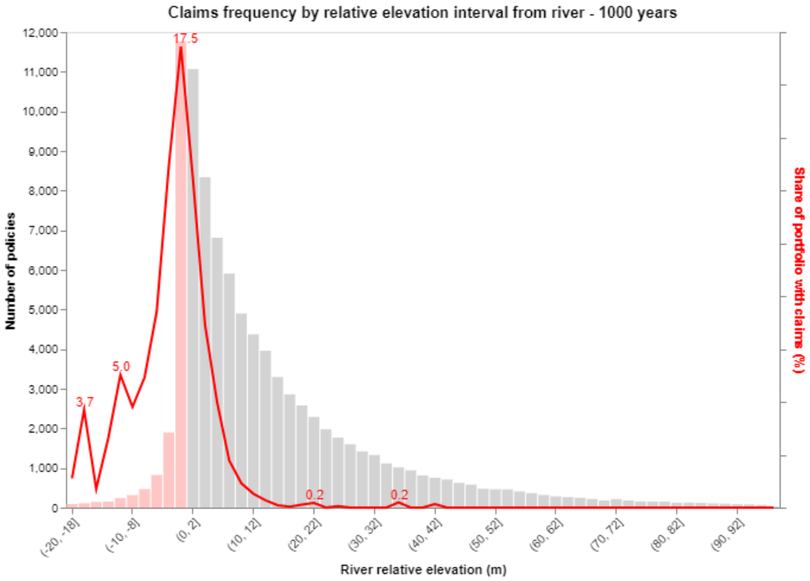


FIGURE 30 DISTRIBUTION OF NUMBER OF POLICIES AND CLAIMS FREQUENCY BY RELATIVE ELEVATION FROM RIVER – FROM CATASTROPHE TOOL, ASSUMING EVENTS WITH SMALL PROBABILITY (ONE-IN-1,000-YEAR)



THE NETHERLANDS

The following figures show that for the Netherlands, there seems to be no correlation between the distance to river and the percentage of addresses in the notional portfolio which is affected by flood events. This percentage is quite stable throughout the different intervals of distance to river (see Figure 31). The same can be said about distance to coastline, where there does not seem to be a pattern in the flood losses observed when looking at different intervals of distance to coastline (see Figure 33).

However, relative elevation to coastline does prove to be a very important variable (see Figure 32). Around 60% of the claims can be attributed to locations with negative relative elevation to coastline. Note that the western half of the Netherlands is elevated approximately around sea level. For this part of the country, relative elevation to coastline is approximately equal to the relative elevation to the nearest river, which is in that part around sea level as well. This measure thus not only captures relative elevation to coastline, but for part of the country captures relative elevation to nearest river as well. Hence, the high explanatory power of the relative elevation to coastline we observe from this figure is also partially explained from the negative elevation to nearest river, and thus aligns with our general expectation that flood risk is higher for addresses which are negatively elevated relative to nearby waters.

FIGURE 31 DISTRIBUTION OF NUMBER OF POLICIES AND CLAIMS FREQUENCY BY DISTANCE TO RIVER – FROM CATASTROPHE TOOL, ASSUMING EVENTS WITH SMALL PROBABILITY (ONE-IN-1,000-YEAR)

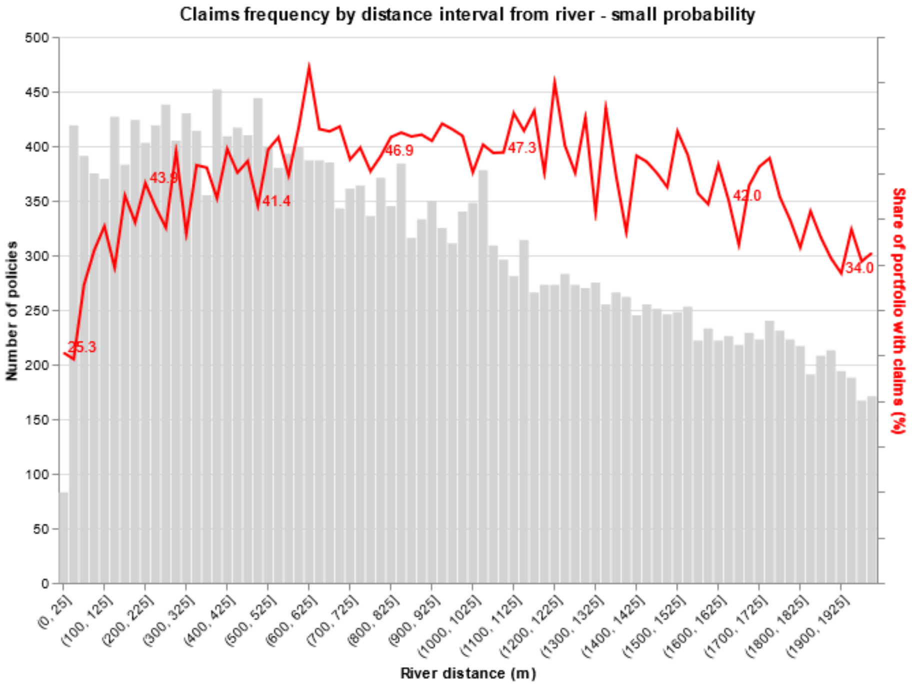


FIGURE 32 DISTRIBUTION OF NUMBER OF POLICIES AND CLAIMS FREQUENCY BY RELATIVE ELEVATION TO COASTLINE – FROM CATASTROPHE TOOL, ASSUMING EVENTS WITH SMALL PROBABILITY (ONE-IN-1,000-YEAR)

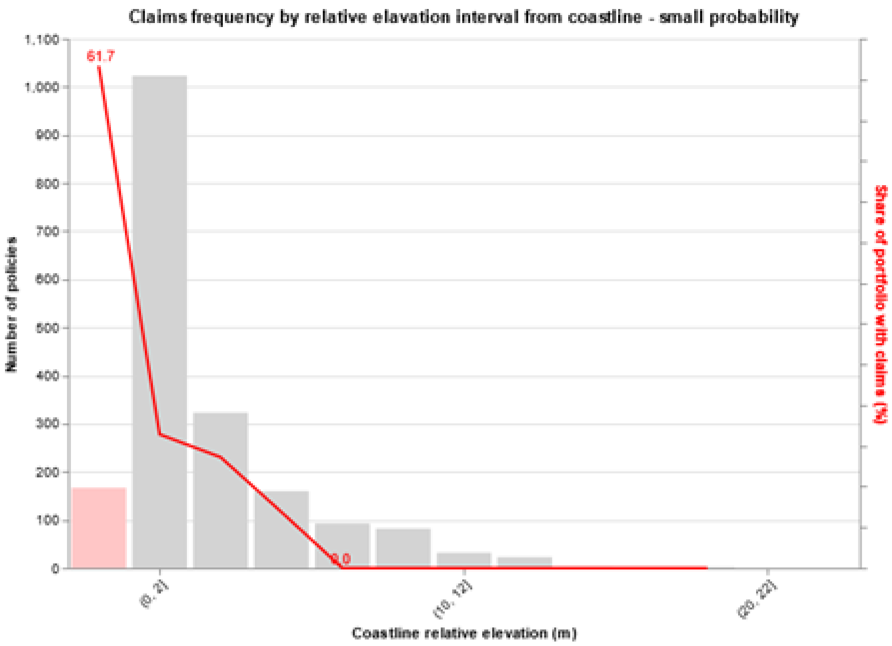
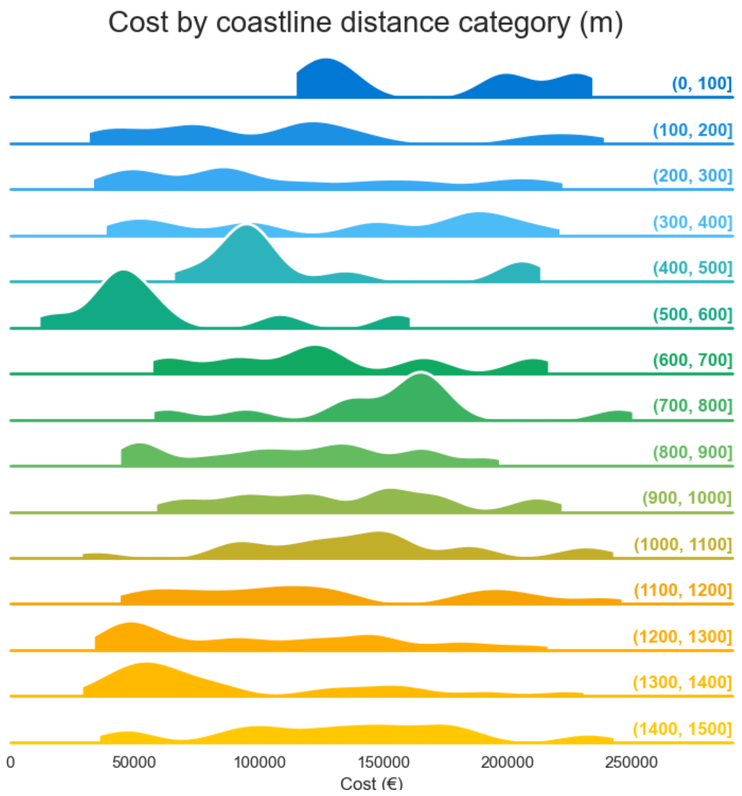


FIGURE 33 DISTRIBUTION OF FLOOD LOSSES BY CATEGORY OF DISTANCE TO COASTLINE – FROM CATASTROPHE TOOL, ASSUMING EVENTS WITH SMALL PROBABILITY (ONE-IN-1,000-YEAR)



Appendix B – Detailed approach

GENERAL APPROACH

The general approach is predicated on the intersection of risk and exposure data along with a damage-curve-based loss function. This approach necessitates an extensive process of data engineering and preprocessing to ensure the integrity and quality of data inputs for our framework. The integration with risk data is achieved through advanced GeoAnalytics techniques, which enable the assignment of specific flood risk measure to each exposure.

This flood risk measure is subsequently converted into an economic loss through the application of a loss function, the details of which will be expanded upon in the subsequent section.

This framework is designed with robust scientific foundation based on GIS industry best practices, yet maintains a level of flexibility, allowing for iterative refinements as new data and insights become available. This balance provides a solution that is scientifically sound and strategically agile. This general approach is independent of the data that is used; however, details of the implementation can depend on the actual data that is available.

In the sections below, specific descriptions of the scenario analysis tool and the catastrophe tool are provided.

SCENARIO ANALYSIS TOOL

This section aims to give a concise overview of the approach taken in the scenario analysis tool, as well as the technical steps taken to perform the geospatial analysis required. The scenario analysis tool at the moment solely considers fluvial flood risk, due to the availability of open data. However, given the right data source, it can easily be expanded to include different other types of floods.

The general goal of the tool is to:

a) Extract relevant characteristics of a portfolio at risk, which can later be used for a more extensive analysis.

b) Determine the annual maximum flood depth per location over the time horizon, for all available models.

c) Using a) and b): calculate the resulting maximum losses and aggregate them to provide insights.

To achieve this, the tool is set up in a modular fashion, allowing extra functionality to be plugged in easily. Such functionality includes, for example, geolocating addresses; calculating distances to rivers, coastlines, or levees; or calculating the elevation of a specific address. When building a pan-European platform such a modular approach is paramount given the lack of universal data sources that span the whole union. This, in combination with the variability in risk factors, requires different data sources and different analysis steps for each country.

The implementation of the framework itself is done in Python and is supported by a variety of open source packages for geospatial analysis such as GDAL and Rasterio. Given that the portfolio is enriched with a variety of extra characteristics and each combination of year, GCM, GHM and RCP scenario contains a potential flood event, there is a need for a solid data storage solution. This solution is found in a PostgreSQL database, supported by the PostGIS extension, which provides a solid and enterprise-grade data storage solution for geographical information systems. This combination offers a flexible base to process a wide range of data sources.

The first step of the framework is to preprocess all required data sources, such that they are available in the database or on the file system and easily processable. This step also projects all data sources to a universal geographic coordinate system, which allows the tool to accurately process all data sources in a universal manner, irrespective of whether they have local or global coverage. Note that for calculation local characteristics such as the distance between an address and its closest river, the data is projected to local geodetic coordinate systems.

Another important part of the preprocessing measures concerns the upscaling of flood depth maps. The upscaling algorithm allows for the reliable enhancement of the resolution of the flood depth input data, making it more granular and therefore better suited for detailed risk analyses. The upscaling algorithm is described in more detail in the section on risk characteristics.

Finally, when all data is available and pre-processed, the flood risk for insurance portfolios can be calculated. If needed, the tool starts by geolocating the addresses given in the input portfolio. The geolocating is done based on local geodetic coordinate systems such as the Rijksdriehoek in the Netherlands or Lambert-93 in France. This step is not needed if the input portfolio already contains geolocations. Then, the main characteristics of each building in the portfolio are determined and stored in the database. Those characteristics include the rebuild value, which is either part of the input data or is calculated from portfolio characteristics.

When the portfolio has been enriched, it is then compared to the flood depth map. This results in a dataset with, for each address and GCM/GHM/scenario, the maximum yearly flood depth for all years between now and 2100. That dataset is further processed to include the losses given those flood depths and the depth-damage function.

Finally, those results are plotted in charts and on maps, to provide insight in the total risks and losses, as well as location and potential for diversification.

CATASTROPHE TOOL

In this section of the paper, we elucidate the implementation of an alternative of the scenario analysis tool described above, leveraging open source GIS software and return-period-based risk data. An in-depth focus on the geographical data processing for this implementation is also presented in this section. This implementation focuses on fluvial and coastal floods due to lack of fine-grained data of sufficient quality for pluvial floods.

The model resulting from this implementation assimilates an insured portfolio from an Excel file, such as CSV, further augmenting it with water height data using GeoAnalytics processing and economic loss data through a loss function across three distinct return period levels describing a flood event. In addition, it computes explanatory risk metrics, including the distance to the river or coastline and the relative elevation to the river or coastline with GeoAnalytics techniques.

This model's construction leverages a processing chain within the open source GIS model builder, from the import of the portfolio input to the downloading of the results output, as geographic data or tabular data for Excel, with a distinct focus on model user-friendliness, optimization and privacy. The user-friendliness of the model is enhanced by the processing chain's ability to include documentation and provide a visualization of each process, including its inputs and outputs. Moreover, when the model is launched, a graphical interface opens, prompting the user to upload their portfolio. Regarding optimization, critical technical decisions have been made, one of which was the choice to work with raster-based geographical risk data, as opposed to vector-based data. While this decision required an in-depth understanding of the data, it resulted in significant time savings.

Indeed, utilizing raster-based geographical data presents several advantages over vector-based data, especially in the context of flood risk modelling. Raster data, represented as a grid of cells or pixels, allows for a more uniform and continuous representation of spatial phenomena. This uniformity is particularly beneficial when modelling natural events such as floods, which do not conform to the discrete, boundary-defined nature of vector data. Additionally, raster data is inherently suited for mathematical modelling and quantitative analysis, as each pixel can hold a value representing information like elevation or flood depth. This allows for more complex spatial and statistical analyses. Moreover, raster data can be more computationally efficient to process, especially when dealing with large datasets or extensive geographical areas. The grid structure enables faster query and analysis times, making raster data a more scalable solution for large-scale flood risk modelling across extensive geographical areas, such as Europe.

However, the process of transitioning from our original vector data to raster can be complex and requires careful consideration. Vector data used in this implementation are polygons representing flood-prone areas with precise boundaries and locations. Converting this to a raster format can lead to a loss of detail and precision, especially if the cell size is not appropriately chosen. This process, known as rasterization, involves assigning a single value to each cell based on the vector data it intersects. The method used to determine this value can significantly impact the accuracy of the resulting raster data. Furthermore, the rasterization process can be computationally intensive, particularly for large vector datasets as the one we used (over 5 Go), and resulting raster may be larger than the vector data, requiring storage optimization. Therefore, while the use of raster data can offer computational efficiency and suitability for flood risk analysis, significant processing must be done accurately to benefit the computational efficiency. From a privacy standpoint, the model ensures complete confidentiality, as the internal data input into the model is never stored, disseminated or reused. This is largely due to the fact that the model and the software used are open source, can be installed locally and operate without an internet connection. Therefore, users can rest assured that their data always remains private and secure.

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