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Beyond the Dikes: Flood Scenarios for Financial Stability Risk Analysis

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Beyond the Dikes: Flood Scenarios for Financial Stability Risk Analysis

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ABSTRACT: We assess financial stability risks from floods in the Netherlands using a comprehensive set of flood scenarios considering different factors including geographical regions, flood types, climate conditions, return periods, and adaptation. The estimated damage from each flood scenario is used to calibrate the corresponding macro-financial scenario for bank stress tests. Our results show the importance of considering these heterogeneous factors when conducting physical climate risk stress tests, as the impact of floods on bank capital varies significantly by scenario. We find that climate change amplifies the adverse impact on banks' capital, but stronger flood defenses in the Netherlands can help mitigate some impacts. Further, we find a non-linear relationship between flood damages and banks' capital depletion, highlighting the importance of considering extreme scenarios.

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WORKING PAPERS

Beyond the dikes: Flood scenarios for financial stability risk analysis

Prepared Caterina Lepore and Junghwan Mok[1]

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1. Introduction

Floods are among the most destructive natural hazards in terms of economic losses. On a global level, according to Swiss Re, global insured losses from floods in the decade through 2022 were more than 88 billion US dollars. Further, these losses were more than 30% higher than those during the previous decade. As climate change can lead to more severe and frequent flood events, these damages might increase even further in the future. How will these damages impact the financial sector? Flood scenarios represent a useful device to answer this question.

Our framework accounts for different characteristics of floods including adaptation. We design a comprehensive set of flood scenarios, including different geographical regions, flood types, climate conditions, return periods, and, most importantly, flood defenses and their reinforcements – one of the key adaptation methods. Despite the importance of adaptation measures, these are often overlooked in climate risk analysis for financial stability due to a lack of data or uncertainties around future adaptation plans. Our paper is the first to capture the impact of flood protections, leveraging data from the Netherlands where flood adaptation has already been legislated based on a forward-looking risk approach. Damages from the different flood scenarios are used to calibrate macro-financial scenarios, incorporating the impact of floods, which in turn are adopted to perform a climate physical risk stress test of the banking sector. Our analysis shows that the impact of floods on financial stability critically depends on the scenario considered.

The framework involves several steps: first, design of multiple flood scenarios leveraging Dutch climate expertise; next, estimating damages from floods using detailed data on economic exposures including residential and commercial buildings and infrastructure. In addition, we calibrate flood scenarios for the Netherlands' neighboring countries – Germany and Belgium – where floods can historically happen at the same time. Then, we aggregate damages and compute nation-wide damages, serving as input to the IMF Global Macro-financial Model (GFM) for generating corresponding macro scenarios incorporating the impact of floods.[1] Finally, the analysis estimates banks' credit losses and resulting capital losses from floods over the next three-year horizon using a stress test model.[2]

Our results show the importance of considering heterogeneous factors influencing flood risk. Overall, we find that the banking sector can cope with credit losses from flood events, but there are differences across scenarios. First, our scenarios cover different types of floods and geographical regions. We focus on flood types A (flooding in unembanked areas) and type B (breaches in primary flood defenses) because they cannot be privately insured. Hence, these types of floods are potentially the most damaging to the banking sector. We cover four independent geographical areas in the Netherlands, representing both coastal and river regions and displaying a high population and economic activity density. Results highlight that floods due to breaches in primary defenses and in the lower river courses are more damaging to the banking sector than floods in unembanked areas and other regions. Floods in neighboring countries do not have large impacts. Second, we consider floods under current and future climate conditions. With the rise in hydraulic loads due to climate

[1] See Vitek (2018) for more details on the GFM model.

[2] The three-years horizon is consistent with standard stress testing exercises used to assess financial stability risks for the banking sector. We note that our flood scenarios under climate change conditions incorporate the impact of future climate conditions in 2050 and 2100. We front-load damages associated with these long-term scenarios into short-term macro financial scenarios. Hence, we assume that these shocks materialize unexpectedly over a shorter horizon.

change, the adverse impact of floods on the economy and the banking sector is stronger.[3] Third, when accounting for reinforcements of flood defenses, as legislated in the Netherlands, we find that the reinforcement reduces physical capital damage from floods. Hence, the adaptation plan serves as an absorber of the adverse impact on the economy. As a result, a lower probability of defense failure mitigates bank credit risks. Finally, extreme scenario, so-called EDO (*Ergst Denkbare Overstromingen*; worst credible floods) lead to significantly larger losses for the banking sector, in the range of 30-60 basis points capital deviation from the baseline. While these scenarios are very severe, with a return period possibly larger than 1 in a million years, they are still considered credible.[4]

This paper contributes to the emerging literature on climate risk stress testing. This literature aims to assess the potential impact of climate change on financial institutions using forward-looking scenarios on transition and physical risks.[5] While work on transition risk stress testing has been developing fast (e.g., Battiston et al. (2017)), the analysis of physical risk has somewhat lagged behind. This is partly due to the complexity of modeling natural hazards and their damages, as well as the lack of geolocational data on financial institutions' exposures. Among the few papers to assess physical risk using geocoded loan-level data, we report Johnston et al. (2023) who analyze flood risks on Canadian residential lending portfolios. Closely related to our work, Caloia and Jansen (2021) and Caloia et al. (2023) look at flood risks in the Netherlands, focusing on their impacts on properties, and, as a result, on banks' loans collateralized by residential and commercial real estate. Overall, they find that flood risks are manageable for Dutch banks.[6] However, in both papers, flood scenarios do not account for climate change or changes in adaptation. We add to these papers by calibrating a more comprehensive set of flood scenarios, covering multiple-breaches floods (in addition to the EDO scenarios), and including the impact of climate change and adaptation as well as floods in neighboring countries.

The approach we use relies on damages from natural hazards aggregated at the country level. These damages are adopted as an input in the IMF GFM macro model to generate macro financial scenarios accounting for losses from climate risks. Specifically, we account for three channels of propagation of physical risk: i) direct destruction of physical capital, ii) Impact on total factor productivity, iii) shock to house prices. The resulting macro financial scenarios can then be used to estimate the impact on banks' balance sheets using standard stress testing models. This is the same approach followed by Hallegatte et al. (2022) to study the impact of tropical storms on the Philippine banking sector and Dolk et al. (2023) to analyze floods and tropical cyclone

[3] Hydraulic loads refer to the forces exerted by water on structures such as dikes, levees, and flood barriers. These forces can be due to various factors including water levels, wave action, current speeds, and the pressure exerted by the water against the protective structures. Hydraulic loads are critical considerations in the design and assessment of flood defenses, as they determine the capacity these structures must have to withstand and safely convey or contain water, thereby preventing flooding.

[4] As explained in Ten Brinke et al. (2010), EDO scenarios represent an upper limit for floods that are still considered realistic or credible by experts in terms of extreme conditions for storm surges, river floods, flood defenses and meteorology.

[5] Transition risks include risks arising from policy, technology, legal, and market changes that occur during the move to a low-carbon economy. Physical risks include risks arising from the increasing severity and frequency of extreme climate change-related weather events (or natural hazards) as well as long-term gradual shifts of climate (BIS 2021).

[6] Caloia and Jansen (2021) show that banks' capital depletions would increase quickly in case more severe floods hit the densely populated western part of the Netherlands. Caloia et al. (2023) extends their framework to adopt a larger set of scenarios. Their estimates show banks' capital declines in the range of 30 to 50 basis points for single breach scenarios and between 40 and 110 basis points for extreme multiple breach scenarios (EDO scenarios).

risks for the banking sector in Mexico.[7] This so called “macro approach” is complementary to “micro approaches” focusing on physical risk at borrower-level.

The key contribution of this paper regards the detailed calibration of flood scenarios, using data from the Netherlands, including adaptation measures. No matter what approach is chosen, the starting point of any physical risk analysis is to define and calibrate scenarios on the evolution of the relevant natural hazards. In this paper, leveraging granular data and detailed methodologies from the Netherlands, we calibrate a wealth of flood scenarios (for a total of 77 scenarios), including different geographical regions, flood types, climate conditions, flood protection standards, and return periods. Most existing studies adopt flood maps that show the potential inundation of a geographical area but are not related to a specific flood event or consider scenarios of individual events, usually based on historical experience. Generally, these scenarios do not incorporate the effect of flood protections nor their change in the future. By contrast, each of our flood B scenarios considers a set of dike breaches that have been selected as plausible under the return period, climate conditions, and flood safety standards. To our best knowledge, we are among the first to explicitly consider the impact of adaptation measures on floods under future climate conditions, leveraging the legislated adaptation plan of the Netherlands.

We also calibrate flood scenarios for neighboring countries. We extend the existing analysis by considering floods not only in the Netherlands, where banks are headquartered, but also in neighboring countries where floods can have spill-over effects on banks with significant exposures (i.e., Belgium and Germany). To do so, we adopt hazard data from a private data vendor, Jupiter Intelligence, and the methodology developed by Fornino et al. (2024) for global physical risk assessments. We note, however, that these flood scenarios are less granular than the ones for the Netherlands. For example, they are not calibrated for specific dike breaches. Damage computation for Belgium and Germany also relies on a proxy for capital due to a lack of data. These caveats highlight some challenges in calibrating physical risk scenarios spanning different countries.

The results should be interpreted with caution given the limitations of the analysis. As in any climate risk analysis, our approach is affected by large uncertainties. For example, the selection and calibration of flood scenarios, particularly under future climate, relies on some expert judgment. Flood scenarios designed with detailed flood maps under future climate conditions would provide a more accurate assessment of both climate change impact and adaptation. Further, while damages from floods are calibrated at a granular level using detailed economic exposure data for the Netherlands, damages are then aggregated at the country level in order to map them to the banking sector via macro-financial scenarios. A complementary approach, used in Caloia et al. (2023), maps damages directly to banks’ balance sheets using loan-level data. Their results show that, under the same EDO scenarios, banks’ capital losses (40-110 basis points) can be larger than our estimates (30-60 basis points). Thus, our approach might be underestimating physical climate risks.

Nonetheless, our framework provides a useful tool to analyze financial stability risks from floods. As discussed by Adrian et al. (2022), economic and financial analysis of the impact of climate change can raise awareness of the risk, and adaptation needs and opportunities. Our framework speaks to these objectives and highlights the importance of adaptation for reducing economic and financial losses from climate change. The framework was used as part of the IMF 2023 Netherlands FSAP to analyze potential risks to financial stability posed by physical risks from floods. The key conclusions drawn were that despite the sizeable land area in the Netherlands susceptible to flooding, the banking sector exhibits resilience to flood events. While the current

[7] See also Lepore and Fernando (2023) for an alternative methodology to calibrate macro-financial scenarios incorporating the impact of physical risks using the G-Cubed model and firm-level data.

impact of floods on the banking sector is limited, climate change can amplify flood-related losses, potentially lowering bank capital ratios in the long run. However, the government's reinforcement plan could help mitigate some of the anticipated losses from climate change. The framework can be adapted to other countries and financial sectors, leveraging their unique set of data and flood characteristics.

The rest of the paper is organized as follows. The next section discusses the Dutch government’s flood risk management strategy, which is an important factor in informing our flood scenario calibration, as described in Section 3. We then explain how to compute economic damages associated with floods for the Netherlands and neighboring counties in Sections 4 and 5, respectively. Section 6 discusses how these damages are used to run a physical risk stress test for the Dutch banking sector. Section 7 presents the results of the analysis, which are further discussed in Section 8. Section 9 concludes. The Annexes contain additional information on the scenarios.

2. Flood Risk Management in the Netherlands

Due to the unique geographic factors, about 60 percent of the land surface in the Netherlands is vulnerable to flooding from the sea, the large rivers, and the lakes. Nearly 26 percent of the surface in the Netherlands is below sea level, land which has been reclaimed from the sea and lakes over the past 800 years. Heavy precipitation is another cause of flooding in the whole of the Netherlands. The ongoing climate change poses a potential threat by increasing sea levels and precipitation, thereby heightening the vulnerability of the Netherlands to flooding.

In safeguarding the nation from flooding, the Dutch government has developed a comprehensive flood protection system. This system comprises polders – a set of dikes, embankments, dunes, and structures that surround reclaimed land or other floodplains along the sea, rivers, or lakes. In addition, strategically placed dams and barriers in rivers and estuaries control water levels and withstand elevated wave heights during extreme conditions. These structures have earned the Netherlands global recognition for its robust water management system.

The flood defenses have been continuously reinforced since the major flood in 1953, including a supporting legal and administrative framework. The flood, which claimed the lives of over 1,800 people in the southwest of the Netherlands, galvanized continuous reinforcements. The legal framework governing flood protection is the Environment and Planning Act (*De Omgevingswet*), which sets safety standards for defenses and outlines the methodology for monitoring barrier strength. It also requires publication of a policy document every six years for reviewing and planning the latest water policy. Additionally, a Delta Programme Commissioner is appointed to oversee the annual Delta Programme, detailing measures to implement water policies. This program involves the collaboration between the central government, provincial and municipal authorities, water authorities, and stakeholders from private sectors and civil organizations.

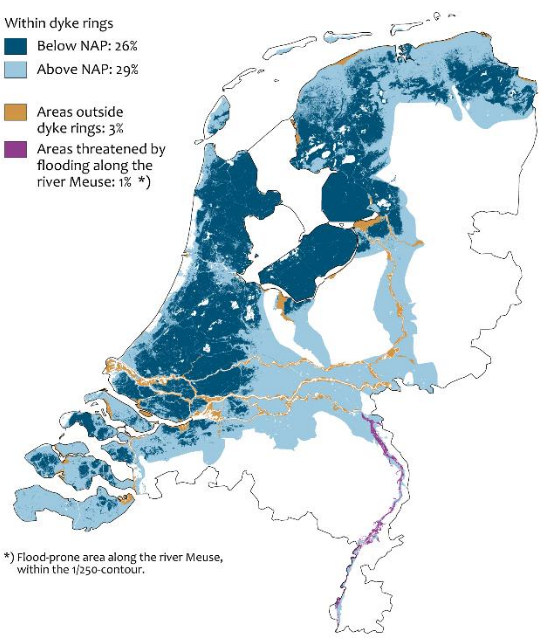
Since 2017 the Dutch flood risk legislation builds upon a risk-based approach, which takes account of both the probability of a flood and the consequences of a flood. The probability of a flood is determined by water level, hydraulic load, strength, and height of the dike (Figure 1). The consequences consist of (direct and indirect) economic damage and (direct and indirect) mortality, which are determined by the flood progress and pattern, and the evacuation rate (Lanz, 2020). The goal of current policies is, by 2050 at the latest, to limit the probability of mortality due to flooding behind the dikes to no more than 1 in 100,000 per year (or 0.001 percent). To achieve this goal, upgrades to approximately 1,500 kilometers of dikes and over 400 engineering structures are planned.

As a consequence of this policy, there is limited insurance coverage for the damages from floods. Private insurers only cover floods caused by local precipitation, canals, streams, or small rivers. Damages arising from the failure of primary defenses, such as large-scale infrastructure and national-level projects designed to prevent flooding, including dikes and the Delta Works, are not covered by insurance. Currently, there is a law in place, so called “Reimbursement for Damages due to Disasters Act” (*Wet tegemoetkoming schade bij rampen; Wts*) that gives the government the opportunity to provide damage compensation in the wake of disasters.

Figure 1. Flood-prone areas and flood probability standards

Nearly 26 percent of the surface in the Netherlands is below the sea level.

Flood-prone Area and Area below Sea Level



Note: NAP (The Amsterdam Ordnance Datum) is a benchmark for measuring sea levels in most of Europe.

Source: Netherlands Environmental Assessment Agency (PBL)

The Water Act sets the flood probability standards for primary defenses.

Maximum Permissible Flood Probabilities

Source: The Netherlands Centre for River studies (NCR)

3. Flood Scenarios

A range of flood scenarios was chosen, encompassing various regions, flood types, climate conditions, and flood protection for different return periods. The corresponding flood maps for each scenario were carefully designed in collaboration with Dutch climate experts from HKV, a private consulting firm, in partnership with the Ministry of Infrastructure and Water Management (MIENW). They provided information on breach locations and the number of breaches occurring at the same time, for different return periods. In the following we discuss the flood scenarios calibration in terms of each of the characteristic considered.

3.1 Regions

The flood scenarios focus on four independent geographical areas in the Netherlands. These areas have been selected from Ten Brinke et al. (2010) on contingency planning for large-scale floods, so-called EDO scenarios. They represent areas that are flood-prone, based on different threats (sea, rivers, lakes), and where floods would cause the largest damage due to higher population and economic activity density/concentration (based on Table 1 in the paper). Among their six regions, the focus is on the following four regions (Figure 2):

- Region I: Southwest and Central Coast
- Region II: Wadden Sea Coast
- Region III: Rhine and Meuse Rivers
- Region IV: Lower River Courses

Two coastal regions, the Southwest and Central coast and the Wadden Sea coast, were selected. A storm surge in the Straits of Dover can affect both the southwest region and the central coast, while a storm surge more to the north can affect the Wadden sea coast. These regions are considered as independent because the likelihood of a flood occurring across the entire coastal zone in the Netherlands is low. For example, extreme conditions from a storm surge in the North Sea cannot simultaneously affect the entire coast.

Two river regions, the Rhine and Meuse and lower river courses, were selected. The Rhine and Meuse represents an area where floods can occur from the largest Rhine branch (the Waal) and Meuse in the central part of the Netherlands. Floods in the lower river courses can result from a combination of peak discharges on the Rhine and Meuse and a storm surge in the North Sea.

Floods in the Rhine and Meuse area can extend to the neighboring countries: Germany and Belgium. This was evident during the 2021 Limburg flood case when flooding in the Rhine and Meuse area coincided with floods in Germany and Belgium. Hence, flood scenarios for this area in the Netherlands will be enhanced by incorporating flood scenarios for Germany and Belgium, focusing on locations near the Rhine and Meuse river basins.

Figure 2. Netherlands' Regions for Flood Scenarios

Region I: Southwest and Central Coast

Region II: Wadden Sea Coast

Region III: The Rhine and Meuse

Region IV: Lower River Courses

Note: The maps illustrate the areas or dike rings susceptible to flooding in each region. It does not necessarily imply that floods occur simultaneously across the entire (dark shaded) area.

Source: Ten Brinke et al. (2010)

3.2 Flood Types

For each of these four geographical regions, two flood types are considered: Type A and B. According to the European Flood Directive Floods are classified into five categories based on the protection, region, and sources of threat (Table 1). This analysis focuses on flood types A and B because they cannot be privately insured and hence are potentially the most damaging for the banking sector. These are the same type of floods that De Nederlandsche Bank (DNB), the central bank of the Netherlands, has focused on for their own physical risk stress testing (Caloia and Jansen, 2021). Their results indicate that flood type B are more damaging relative to flood type A. However, they do not incorporate granular (geolocational specific) flood scenarios or account for future climate conditions; instead, they rely on a grid of increasingly severe inundation depths for these two types of floods.

Table 1. Flood Types Classification

Type	Description
A	Flooding in unembanked areas
B	Breaches in primary flood defenses
C	Breaches in regional flood defenses
D	Flooding from bank overflow by regional water bodies
E	Water on streets due to extreme rainfall

Additionally, EDO scenarios are included as a separate flood type, representing extreme scenarios. We note though that they categorically align with type B floods since they result from breaches in flood defenses. These EDO scenarios are designed for contingency planning, focusing on potential future events rather than what has already happened. According to Ten Brinke et al. (2010), there were meetings with Dutch experts on meteorology, storm surges, river floods, and flood defenses of provinces, water boards, the state (*Rijkswaterstaat*) and research institutes to define the worst credible flood scenarios. The possible hydrodynamics (water level, wave height and duration) and the possible number, locations, and size of the breaches in the flood defenses were decided based on expert judgement. The scenarios are independent of the likelihood of these floods' occurrence, making it challenging to express them in terms of return periods, possibly extending to 1-in-1,000,000 years or more.

3.3 Climate Conditions and Flood Protection

For each region and flood type, current climate and future climate conditions are considered. Future climate conditions are considered under the Dutch scenario, so-called W+ (from the Royal Netherlands Meteorological Institute (KNMI) KNMI'14 scenario), which broadly aligns with the RCP 8.5 (IPCC 5th Annual Report).[8] In KNMI'14 scenarios global emission from the IPCC 5th Annual Report are converted to the Netherlands up to 2100.[9] Although flood depth maps under *current* climate conditions are available, there are currently no estimates for flood depth maps under *future* climate conditions. In the collaboration with flood risk experts from HKV and MIENW, the impact of future climate conditions on flood scenarios and associated damages are considered under specific assumptions described below.

For flood type A, the water level under higher return periods is considered as that under future climate conditions. Kolen et al. (2022) find that the return periods of water levels in most water systems decrease by approximately a factor of 3 in 2050 W+ and by about a factor of 10 in 2100 W+. In other words, the exceedance probability of a water level increases by a factor of 3 and 10 respectively. Leveraging these findings, the flood maps for 2050W+ and 2100W+ are generated by applying the current flood depth maps with different return periods: 1-in-10, 1-in-100 and 1-in-1,000 years (as higher return periods than 1-in-10,000 years are not available for current climate).

For flood type B, the analysis needs to account for both the impact of future conditions on hydraulic loads as well as the future reinforcement of flood defense, as these floods arise from breaches in flood defenses. By legal mandate, primary flood defenses in the Netherlands will be reinforced to meet the floods safety standards at the latest in 2050 to account for climate change and socio-economic developments. For this reason, scenarios for flood type B incorporate both future climate conditions in 2050 with and without these safety standards reinforcements. The strength of flood defenses is expressed in terms of return periods, representing the acceptable failure probability, which varies by location and depends on the impact of flooding and the costs of reinforcement. Table 2 presents the scenarios for flood type B.

Table 2. Scenarios for Flood Type B

Scenario Name	Failure Probability (Reinforcement)	Hydraulic Loads (Climate Conditions)	Description
B1	Current Situation	Current Situation	Readily available flood water depth map
B2	2050 Safety Standard	2050 (W+)	Combined effects of reinforcement and climate changes
B3	Current Situation	2050 (W+)	Impact of climate changes on current failure probability

[8] While a new set of climate scenarios for the Netherlands was published in October 2023 (KNMI'23), the estimates of water levels or hydraulic loads based on these scenarios were not available at the time of this analysis. KNMI'23 is aligned with the sixth assessment Report (AR6), and the scenarios are based on the amount of greenhouse gas emissions (and therefore global warming) and the degree of precipitation change in the Netherlands. (https://www.knmi.nl/kennis-en-datacentrum/achtergrond/knmi-23-klimaatscenario-s)

[9] For more information on the KNMI'14 scenarios we refer to Attema et al. (2014).

3.4 Return Periods

We consider a range of conservative return periods. For flood type A the analysis considers return periods of 1-in-10, 1-in-100, 1-in-1,000 and 1-in-10,000 years as explained in the previous section. For flood type B, the analysis considers return periods of 1-in-100, 1-in-1,000 and 1-in-10,000 years. These are the return periods suggested by HKV and considered in the Netherlands for flood protection standards.[10] For each region and return period, the maximum number of possible and realistic simultaneous breaches are specified based on the study by Kolen and Nicolai (2023). It is assumed that these numbers are consistent across the three cases considered above. In case of a 1-in-100 years return period in the Southwest and central coast and Wadden sea coast, no breaches occur, resulting in no damages.

Table 3. Numbers of Breaches by Region and Return Period

Region	Return Period		
	100	1,000	10,000
I: Southwest and Central Coast	0	4	7
II: Wadden Sea Coast	0	4	7
III: Rhine and Meuse Rivers	1	3	4
IV: Lover River Courses	1	3	3

Source: Kolen and Nicolai (2023)

For every scenario outlined in Table 2, the selection of breach locations and return periods varies. In B2, lower failure probabilities under the 2050 safety standards lead to different breach locations compared to those in B1. However, the return periods are higher than B1, as it is adjusted to the 2050 W+ climate condition. On the other hand, since B3 has the same failure probability as B1, the breach locations are also the same, but with higher return periods.

In the combined scenario involving floods in the Netherlands as well as Germany and Belgium, only floods with a return period of 1-in-100 years are taken into account due to data limitations in those countries. Unlike the Netherlands, we do not possess detailed flood information from local climate experts in Germany and Belgium. Instead, water depth maps are obtained from the private data vendor Jupiter Intelligence. The detailed methodology for selecting flooded area and calculating damages is elaborated in the next section.

Based on the outlined scheme, a total of 77 flood scenarios have been designed. Figure 3 provides a summary of the scenario design scheme introduced in this section. Water depth maps for certain return periods are unavailable due to the earlier described assumptions. A more detailed list of scenarios is presented in Tables A-1-A-4 in the Annex II.

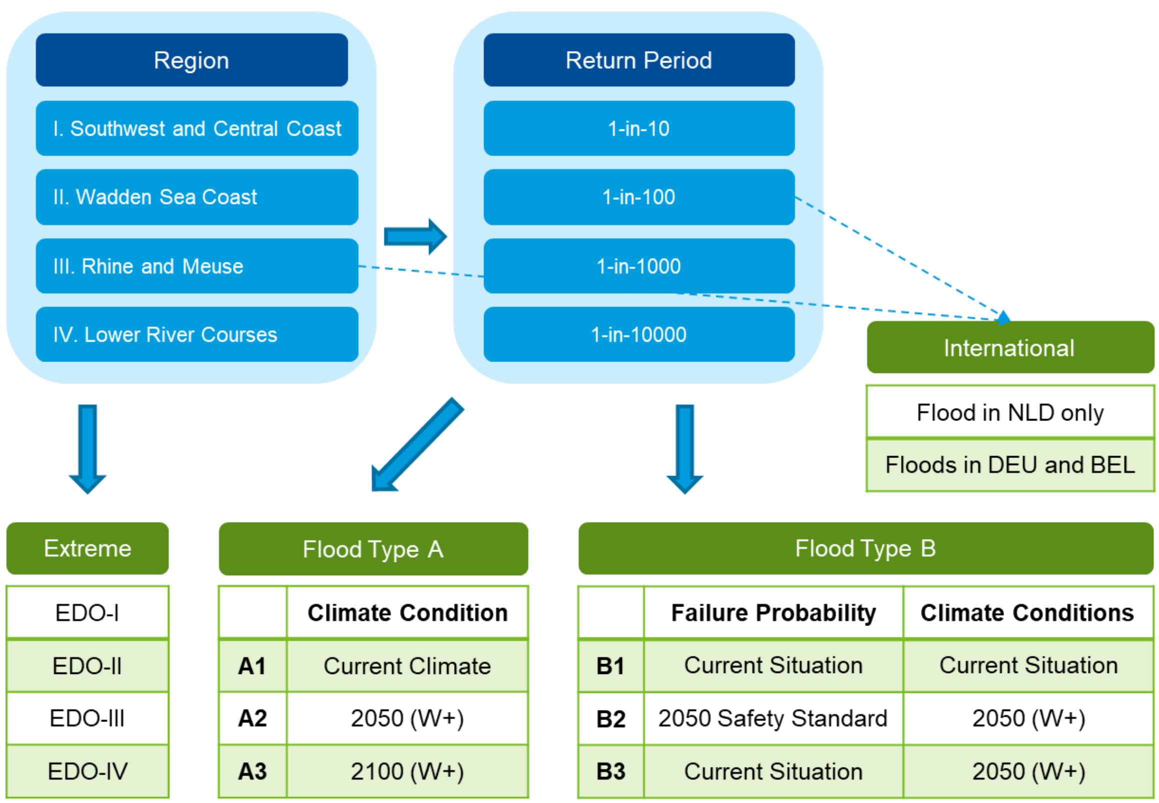
Water depth maps for the Netherlands are retrieved from the LIWO (National Water and Flood Information System) database for each breach location. [11] Using the information on breach locations and return periods

[10] As noted in Jorissen et al. (2000), the statutory safety levels (expressed as return periods) in the Netherlands are quite high compared to safety levels in other countries.

[11] LIWO database can be found at https://basisinformatie-overstromingen.nl/liwo/#/maps.

provided by flood risk experts from HKV and MIENW , corresponding flood water depth maps are generated. If there are multiple breaches in a scenario, the water depth maps are manually combined using Geographic Information System (GIS Software).[12] In cases of overlapping inundated areas on the maps, the maximum level of water depth is selected.

Figure 3. Flood Scenario Design Scheme



4. Damages Estimation

The Deltares methodology of the Netherlands, also known as the Standard Method 2017, is employed to estimate flood damage and casualty. This methodology was used to establish the water safety standards that were legalized as of 1 January 2017 (Slager and Wagenaar, 2017), and it has been continuously updated and

[12] Although the LIWO database offers water depth maps for scenarios involving multiple breaches, it does not allow the download of raster files, hindering the calculation of damages.

improved based on new data. In this analysis, the latest version of the software, Schade Slachtoffer Module (SSM; Damage and Casualty Module), which operates the Standard Method, is employed.

The SSM software contains granular data on real estate or objects located at each geographical grid.[13] The information includes the number of objects or area, location, type of buildings, maximum damage per the number of objects/m^2, and more. This information serves as an input to calculate flood damages, combined with the flood water depth map from each scenario. Damages can be estimated for different type of exposures, namely business, residence, infrastructure, and other (Table 4).[14,15]

Using the SSM data and methodology, we compute the total direct physical damages for each flood scenario. As our interest lies in the impact of capital shocks to the macroeconomy, only direct damages are considered – physical capital loss resulting from direct physical contact with the flood – while excluding indirect damages, such as those associated with business interruption.[16]

The total flood direct physical damage under each scenario is calculated by multiplying the maximum flood damage per object or m^2 for each category, with the damage factors and the number of objects or m^2 affected by floods. The maximum flood damage represents the cost to reconstruct the building/infrastructure. The damage factor gives the percentage of the maximum damage which occurs given a certain water depth. The total direct physical damage under a scenario s, is calculated by:

$$Damage_s = \sum_{i=1}^{N} \alpha_{is}\, n_{i,s} S_i,$$

where:

- $\alpha_{i,s}$: damage factor of category i given a certain water depth,
- $n_{i,s}$: number of objects or m^2 in category i affected by floods,
- S_i : maximum damage per object or m^2 in category i affected by floods,
- N : total number of categories.

The damage factor α_i is determined from damage functions that vary across exposures categories (and subcategories), calibrated specifically for the Netherlands. With increasing water depth, the damage factor increases from 0 to 1. Some examples of damage functions for each category and subcategory are presented in Figure 4. The consequences of floods outside the dikes differ from the floods that occur within the dike. This

[13] The data can have the geographical resolutions of 5m, 25m, 50m and 100m grids.

[14] For business and residences, the source data is the Basic Registration of Addresses and Buildings (BAG) 2022 and buildings and residence objects (ESRI file geodatabase, www.esri.nl). For infrastructure, road data is from the National Road File (NWB-Wegen 2022) via the national georegister Netherlands (www.nationaalgeoregister.nl), and railway data is from the Top10NL (2022) files which also take into account various light-rail connections, metro and tram tracks. A full description of the software and data source can be found at https://iplo.nl/thema/water/applicaties-modellen/waterveiligheidsmodellen/schade-slachtoffer-module/.

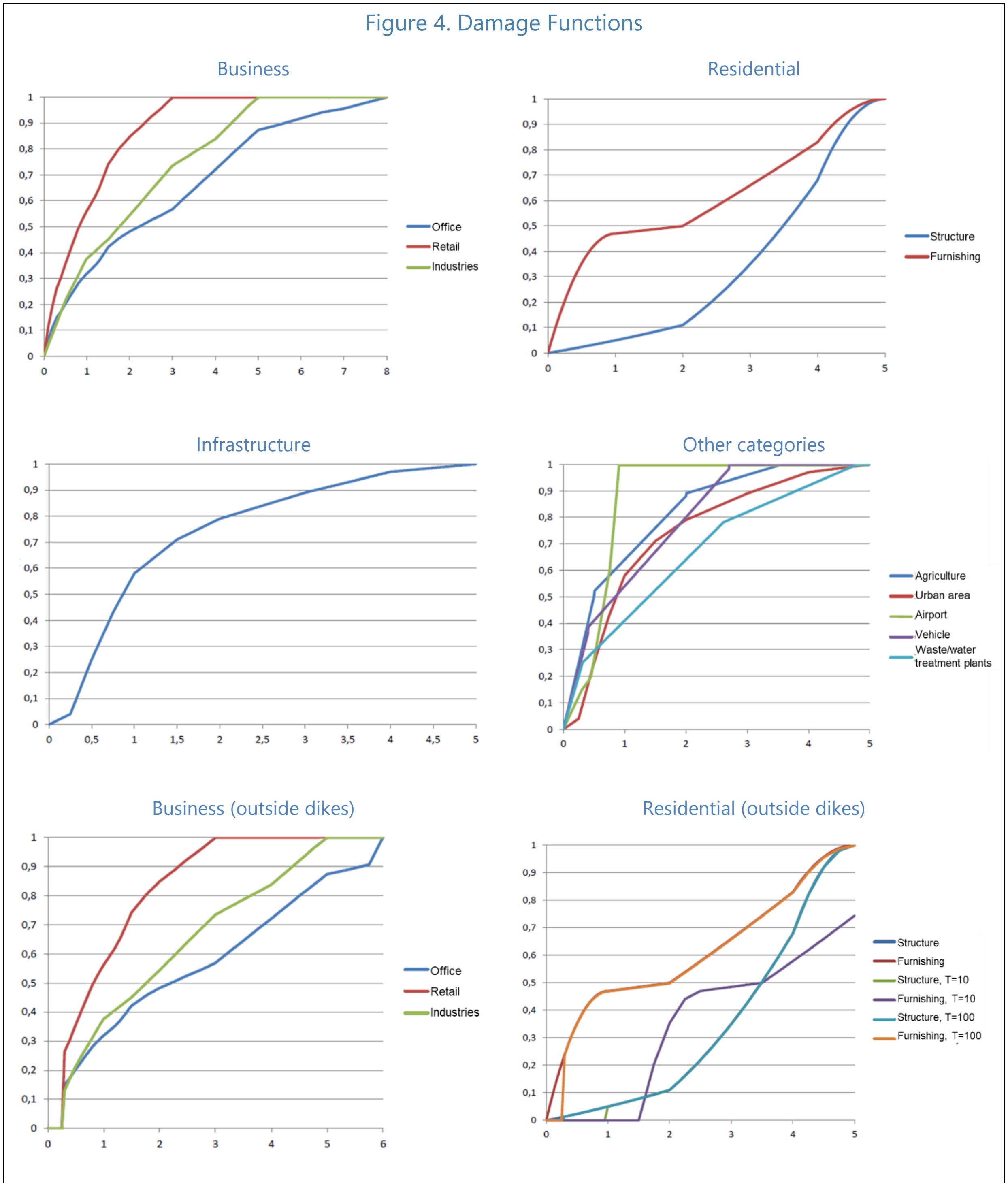
[15] In addition, the SSM software also considers some special objects. There are 4 main categories of special objects: vulnerable objects, national monuments, IED installations and protected areas according to the Water Framework Directive (WFD). For these objects and areas, only affected numbers or areas are reported and no damage is calculated.

[16] The SMM software also calculates the expected casualty caused by floods, using a mortality function with water depth, water flow rate, rate of ascent, inhabitant data as inputs.

is mainly due to the limited size (both area and water depth) and the expectation that objects and inhabitants are adapted to flooding to a certain extent (Slager et al. 2013). That is why some adjustments, mainly in terms of damage functions, have been made to the outside dike method. For instance, for houses outside dikes it is assumed that a number of structural measures, such as no basement, laying stone floors, have been taken in the outer dike area where high water occurs with some regularity.

Each category has a maximum damage S_i, calibrated based on the Statistics Netherlands macro data at national level. Table 4 displays the amount of maximum direct damage per unit and corresponding units for each category. These values are periodically updated to reflect changes in property values and the number of properties.

Finally, we compute the Netherlands' capital shock, or damage rate, as the percentage of estimated direct physical damage to the (pre- damage) total capital value. Estimating the total capital value in the Netherlands is challenging, so a proxy is devised. First, a hypothetical flood map is generated with 10 meters of water depth, assuming that the entire surface of the Netherlands is submerged. Then, the damage from this hypothetical flood can be calculated using SSM. This damage amount can be interpreted as a proxy for the total capital value in the Netherlands.



Note: The horizontal axis is water depth(m) and the vertical axis is damage factor. The damage functions for residential real estate outside dikes are differenciated by return periods (T=10 and T=100)
Source: Butcher and Wagenaar (2017)

Table 4. Categories and Maximum Damage in SSM2017

Categories		Direct damage	Indirect damage	Maximum Direct damage (€/unit)	Unit
Business	Meeting facilities	X	X	194	m^2
	Office	X	X	1,607	m^2
	Health services	X	X	2,689	m^2
	Industries	X	X	1,420	m^2
	Education facilities	X	X	1,228	m^2
	Sport facilities	X	X	113	m^2
	Retail and Commerce	X	X	1,796	m^2
Residential	Single family houses - Structure	X	X	1,295	m^2
	Single family houses - Furnishing	X		81,985	obj.
	Ground floor apartments - Structure	X	X	1,295	m^2
	Ground floor apartments – Furnishing	X		81,985	obj.
	First floor apartments – Structure	X	X	1,295	m^2
	First floor apartments – Furnishing	X		81,985	obj.
	Higher floor apartments - Structure	X	X	1,295	m^2
	Higher floor apartments – Furnishing	X		81,985	obj.
Infrastructure	Regional roads	X		2,243	m
	Motorways	X		1,520	m
	Other roads	X		414	m
	Railroads – electrified	X		1,710	m
	Railroads – unelectrified	X		6,842	m
Other Categories	Agriculture	X		2.36	m^2
	Green house	X		63.1	m^2
	Recreation intensive	X		17.22	m^2
	Recreation extensive	X		13.98	m^2
	Urban area	X		76	m^2
	Airport	X		185	m^2
	Vehicle	X		10,491	obj.
	Pumping stations	X		1,177,853	obj.
	Waste/water treatment plants	X		17,107,030	obj.

Note: Maximum direct damage in this table is damage from floods within dikes only.
Source: De Bruijn et al. (2015) and SSM2017 v4.1 (2023)

5. Floods in the Neighboring Countries

Damages from floods in Belgium and Germany are estimated using a similar methodology, developed in a global study on flood's damages (Fornino et al. (2024)). Specifically, flood depths and fraction flooded data are retrieved from Jupiter Intelligence for a 1-in-100 years return period under SSP5 RCP 8.5 scenario in 2050. The methodology uses the damage functions for floods in Europe calibrated by Huizinga et al. (2017) and the gridded GDP data from Murakami et al. (2021) as economic exposures.

The aggregate country-level damage rate of country c (D_c) is calculated as:

$$D_c = \sum_{i=1}^{n} d_{i,c} * \frac{GDP_{i,c}}{GDP_c}$$

where:

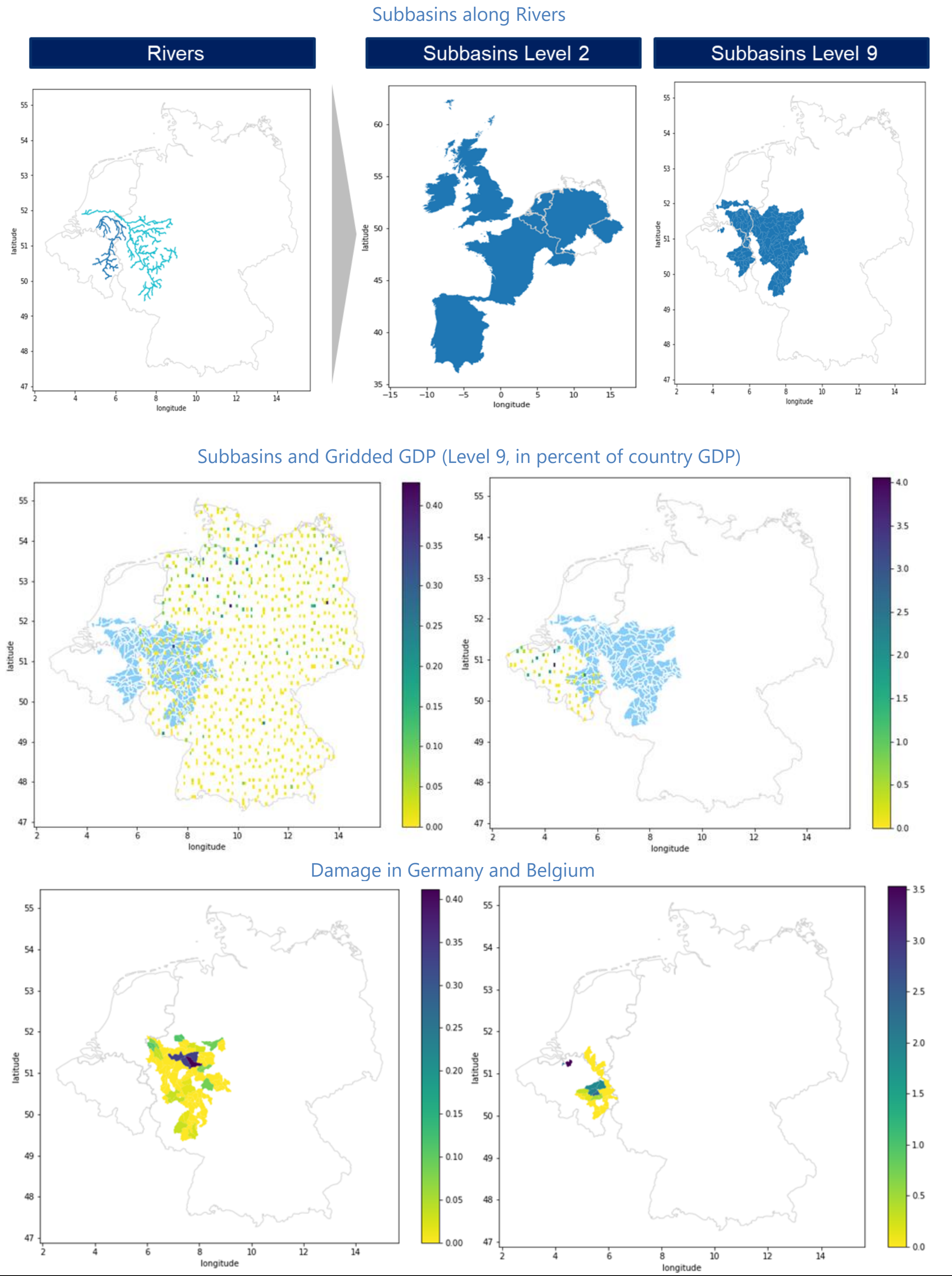
- $d_{i,c}$: the damage rate for location i[17] in country c, as $d_{i,c} = frac_{i,c} \times df_{floods}(depth_{i,c})$,
- df_{floods}: damage function in Europe from Huizinga et al. (2017),
- $frac_{i,c}$: fraction of flooded area within location i from Jupiter Intelligence,
- $depth_{i,c}$: flood depth in location i from Jupiter Intelligence,
- $GDP_{i,c}$: gridded GDP in location i from Murakami et al. (2021),
- GDP_c: the total GDP of country c.

For each grid, the GDP exposure is divided in built-up and non-built-up, using the land cover data Copernicus Global Land Operations "Vegetation and Energy" (CGLOPS-1) for 2019 from Buchhorn et al. (2020). Built-up areas refer to the land used for human habitation, such as buildings and other manmade structures, while non-built-up areas include forest, water, and other nature. For built-up areas, the residential, commercial, and industrial damage functions are combined, by equally weighting each function, while for non-built-up agriculture and infrastructure damage functions are considered.

Due to the lack of more granular flood data in Germany and Belgium, the inundated locations are selected as follows (Figure 5). First, the subbasins along the Rhine and Meuse rivers are divided into different levels of granularity. Then, the flood depth and the gridded GDP within each subbasin (level 9) are used as inputs for damage functions to calculate the flood damage rate for each subbasin. While the damage rates across subbasins are obtained, it is unrealistic to assume that floods occur simultaneously in all subbasins. Hence, a damage rate is selected from the distribution of damages across subbasins, considering the size of damages from historical events.

[17] Location i refers to an area where both flood depths and gridded GDP data are available at a certain level of granularity. For example, in para 33, each subbasin is treated as a location.

Figure 5. Damage from Germany and Belgium



While this approach allows for the calculation of damage rates from flood scenario, there is a caveat concerning the consistency of GDP and capital stock shock. The damage rate is calculated in terms of GDP losses, even though the macro model uses a damage rate of capital stock as an input for a non-linear production function. This implies that the GDP loss rate might differ from the capital damage rate unless the production function is a perfect linear function. This limitation could result in an underestimation of impacts on macro variables.

6. Banking sector stress test

This analysis adopts a stress test model to examine the impact of flood damages on the banking sector. The approach relies on aggregating granular flood damages, produced following the methodology explained in Section 5 above, at the country level and using them to calibrate macro-financial scenarios including the impact of floods, as explained in Subsection 6.1 below. The scenarios are then used to estimate the credit risk impact for banks, using PDs and LGDs models (see Subsection 6.2).

6.1 Macro-financial scenarios

The IMF Global Macro-financial Model (GFM) has been used to generate macro scenarios spanning three-year horizons by using shocks calibrated from the flood scenarios. Although damages from flood scenarios considering future climate are estimated based on flood risks in year 2050 or 2100, damages can also materialize within the short horizon, albeit with a substantially low probability. While this is a strong assumption, climate stress testing exercises by many central banks and regulators adopt similar approaches.

Similar to Hallegatte et al. (2022) and Donk et al. (2023), the following three shocks are considered:

1. Direct destruction of physical capital. The total damage rate from floods, aggregated at country level for the Netherlands, Belgium, and Germany, serves as an immediate direct shock to the capital stock.
2. Impact on total factor productivity (TFP). The shock to TFP arises from the direct damages to the capital stock. This is calibrated at twice the total damage rate and assumed to be persistent, aligning with evidence from the literature.
3. House prices shock. The shock to house prices is calibrated using the ratio of direct damages for all residences relative to the maximum damages for residences multiplied by the number of residences. Given the regional nature of floods, the house damage rate is adjusted by multiplying the elasticity of regional house prices changes to overall house price changes. Due to the data limitation of the regional house damage estimates in Germany and Belgium, the house price shock is only imposed on the Netherlands.

6.2 Banking sector credit risk modelling

The analysis focuses on banks' loan portfolios and the associated credit risks under the simulated macro scenarios. The stress test methodology considers the following loans' categories for six Dutch Systemically Important Institutions (SIs): mortgage, corporates, other retails, financial institutions, government, and qualifying loans. We also distinguish banks' loans by countries: the Netherlands, Germany, Belgium, UK, United States, Australia, and the rest of the world.[18] Banks' data as of June 2023 was sourced from confidential regulatory reporting, specifically the common reporting (COREP) and financial reporting (FINREP). These datasets were complemented by PDs historical series provided by the DNB.

The simulated macro scenarios are used to stress PDs and LGDs of each bank. Leveraging the historical relationship between PDs and macro variables, future trajectories of PDs are projected of each loan category under each macro scenario. House price shocks are used to project LGDs for collateralized loans, while LGDs for uncollateralized loans are expressed as a function of PDs.

The analysis specifically focuses on the credit risk channel. While acknowledging that other risk channels, such as interest rate risks and market risks, also contribute to transmitting physical risk shocks, this analysis narrows its focus on the credit risk channel, recognizing it as a main driver of the overall impact of shocks on bank capital. This approach allows for assessing the first-order impact of damages on banks' credit losses, emphasizing the perspective of physical capital damages. However, it is important to note that this approach has the caveat of possible underestimation of impacts due to the exclusion of other channels.

The credit risk analysis projects credit impairments of banks' loan portfolios under the baseline scenario and scenarios including flood risks. The analysis models scenarios-dependent trajectories of probability of default (PD) and loss given default (LGD), accounting for provisioning rules prescribed by International Financial Reporting Standard 9 (IFRS 9).

We estimated the historical relationship between the banking sector PDs and macrofinancial variables by portfolio and country of exposure, using a panel regression model with system-wide PDs by portfolio and country.[19] We then projected the forward-looking PD paths conditional on the macroeconomic scenario.

For mortgage, other retail, qualifying revolving, and corporate portfolios, a Panel Autoregressive Distributed Lag (ARDL) model in equation (1) is deployed. The logit-transformed probability of default is explained by its 1-period lag, a group of exogenous variables and their lags z_{t-s} (Equation (1)). z_t include the standard explanatory variables, e.g., economic growth, interest rate, housing price growth, and real wage growth underpinning the scenarios. A fixed effect α_i captures the unobserved country-specific characteristics.

$$ln\left(\frac{PD_{i,t}}{1-PD_{i,t}}\right) = \alpha_i + \lambda \cdot ln\left(\frac{PD_{i,t-1}}{1-PD_{i,t-1}}\right) + \sum_{s=0}^{P} \beta_{i,s}\, z_{t-s} + u_{i,t} \qquad (1)$$

The econometric analyses reveal that economic growth is an important factor to explain the PD variation. Housing price growth affects mortgage portfolios and to some extent the retail portfolios through wealth effect. Interest rate rises are only felt with a lag, more so for mortgage loans which tend to be long-term and with fixed rates in the Netherlands. Wage growth is a positive factor for sustaining retail borrowers' credit quality, but CPI inflation erodes their purchasing power. CPI inflation outpaces wage growth in the adverse scenario, thus eroding household's debt service capability. Corporate portfolio benefits from a positive export growth. Credit spread is a significant predictor for corporate creditworthiness.

[18] The IMF Global Macro-financial Model allows to calibrate macro-financial scenarios for all these countries, accounting for the flood related shocks in the Netherlands, Germany and Belgium described in Section 6.1.

[19] System-wide PDs refers to the average of the PDs for the six Dutch Systemically Important Institutions weighted by banks' exposures in our sample.

The PDs of government and financial institution are computed using a structural model, in equation (2). The choice of this structural model is due to the low occurrence of default events and significant impact by idiosyncratic factors in the two sectors.

$$PD_{i,t} = \left(\frac{Credit\ spread_{i,t}}{1 - Recovery\ Rate}\right) \qquad (2)$$

System-wide PDs are then transformed to bank-specific PDs by assuming constant differential of risk between the aggregate banking system and an individual bank holding the same portfolio. Specifically, by computing the distance-to-default of both aggregate and bank-specific PDs as of 2022. This is done taking the inverse normal of the two values. The difference of the two was assumed to stay unchanged throughout the stress testing horizon. The bank-level PDs can be implied accordingly.

We estimated LGDs using two structural models. For the secured portfolio, we derived the LGD trajectories using bank-specific LTV projections and several other cost factors (Gross et al., 2020). For the unsecured loans, the LGDs were modelled as a function of future PDs (Frye and Jacobs, 2012; Frye, 2013).

The IFRS9 accounting rule requires banks to provision for expected credit losses by loan stage. We first estimated the bank-specific transition matrices by sector, i.e., household, corporate, government and institution, using historical information on loan movements across stages supplemented by statistics directly provided by the authorities. We then adjusted the transition probabilities with scenario-conditional PDs from the “satellite models” (“beta-linking” approach, Gross et al., 2020) and inferred the outstanding loan amount by stage over the stress-testing horizon. We finally computed the 12-month provision for stage 1 loans, and lifelong provision for stage 2 and 3 loans. Write-off rate is assumed to be zero.

7. Results

We estimated damages from floods for all 77 scenarios described in Section 3. Results are reported in the Annex II in terms of capital and house price shocks. Capital shocks range from 0.001 percent of total capital, under the A1 flood scenario with 1-in-10 years return period in regions I and II, to 0.912 percent under the B3 flood scenario with 1-in-10,000 years return period in region III. The local nature of floods limits the overall damage to physical capital compared to the country's total capital stock. In terms of house prices damages are more material, ranging from 1.46 to 24.71 percent under the A1 flood scenario with 1-in-10 years return period in region I and III respectively. Overall, comparing damages across scenarios, we make the following general observations.[20] First, comparing floods’ A and B damages - for the same 1-in-1000 year return period and same geographical region - we observe that damages for floods type A tend to be significantly smaller than floods type B. Second, damages tend to be higher under future climate conditions relative to current. Third, adaptation – as in dike reinforcements for flood type B – tend to reduce damages.

Out of the 77 flood scenarios, 12 scenarios are selected to include all flood types, all regions, different climate conditions, and reinforcement at least once in the stress test exercises. Annex I shows the water depth in the

[20] There are some exceptions to these results due to the scenarios’ calibration, for example the choice of specific breaches’ locations for flood type B.

locations affected in the Netherlands for these selected flood scenarios. Using these selected 12 scenarios, the following stress test exercises are considered to evaluate their impacts on banks' capital[21,22]:

1. Impact of climate change in the unembanked area (Region IV),
2. Impact of climate change and reinforcement (adaptation) in the embanked area (Region II),
3. Impact of extreme flood scenarios (EDOs) across all regions,
4. Impact of floods in the neighboring countries (Region III).

Overall, credit losses from floods are modest for the Dutch banking sector. There are however significant differences in the effects across type of floods and scenarios as explained in the following.

7.1 Impact of climate changes in the unembanked area

First, we assess the impact of climate change in the unembanked area, focusing on the 1-in-1000 year flood in the lower river courses region (Region IV). Region IV is selected as a representative case because of its higher capital damages incurred compared to other regions for this return period (see Annex II). While floods in Regions I and II occur due to storm surges in the sea, floods in Region III and IV typically occur due to both storm surge and river floods. Consequently, the flood duration in Region III and IV is longer, resulting in higher damages.

With the rise in hydraulic loads due to climate change, the adverse impact of floods on capital stocks and house prices are stronger. As a result, the impact on banks' credit risk and capital is also more pronounced. In particular, banks' PDs for the mortgage portfolio rise to 2.30 and 2.36 by 2025 under the future climate scenarios, relative to 2.15 and 2.07 under current climate and the baseline scenarios (see Figure A-4 in Annex III). The flood under the current climate condition causes an additional 11 percent credit losses compared to the baseline scenario in 2023, and the magnitude of losses increases in the future climate scenarios (to 13.5 in the 2050(W+) and to 14.7 in the 2100(W+) scenarios). In the 2100(W+) scenario, floods reduce the bank capital ratio by 0.09 percentage points in 2023 relative to the baseline (Figure 6). No bank's capital ratio falls below the capital requirement in all scenarios.

Overall, these types of floods do not lead to significant damages and capital depletion for the banking sector. Caloia at al. (2022) finds similar results. This is because type A floods' water depth is not usually great and these floods are in areas which are not densely populated like river meadows, beaches and some inhabited areas, hence are not protected by law from flooding. Even if we focus on the region with the highest damages from floods in our analysis, these types of floods do not lead to important losses from the banking sector.

Figure 6. Impact of Climate Changes in the Unembanked Area

[21] All results are reported as the capital loss, or credit loss, deviation from the baseline scenario, unless specifically stated. The baseline scenario is calibrated based on the April 2023 IMF World Economic Outlook (WEO). This baseline scenario does not include any (explicit) shock from floods.

[22] The macro approach, which adopts country-level damages (aggregated from granular location specific damages), ignores regional macro dynamics and the regional distribution of banks' loans. However, it is challenging to estimate different macro impacts on flooded and non-flooded regions without granular loan-level data and a dedicated regional model.

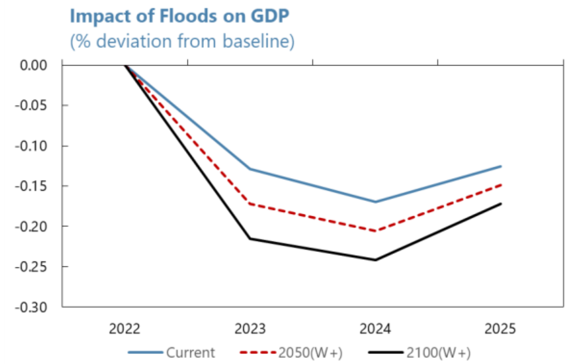
Climate changes magnify capital and house price shocks…

Capital and House Price Shock by Scenario

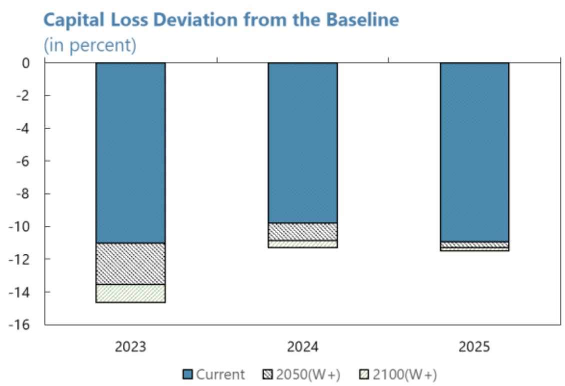
Return Period: 1,000 years

Scenario		Capital Shock	House Price Shock
A1	Current	0.020	1.26
A2	2050(W+)	0.032	1.48
A3	2100(W+)	0.044	1.70

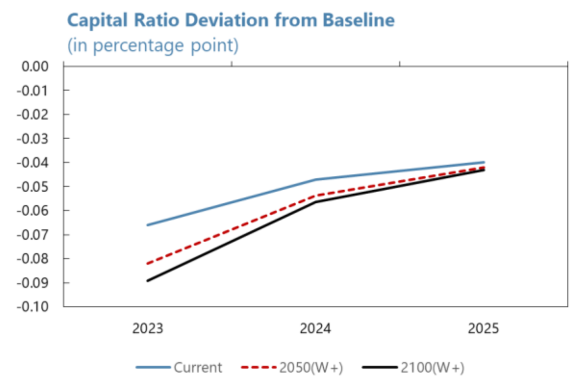
… as well as the adverse impacts on GDP.



The reduction rate of bank capital loss increases under the future scenarios.



The bank capital ratio drops but stands above the capital requirement.



7.2 Impact of climate changes and reinforcement (adaptation) in the embanked area

This analysis evaluates the impact of floods under both current and future conditions in the embanked area and disentangles it into the effects of climate change and adaptation. The transition from B1 to B2 scenarios quantifies the difference in impacts between the current and future conditions. During these periods, hydraulic loads increase due to climate changes, and the government reinforces the flood defense system to adapt to climate changes. Keeping the climate condition constant, the difference between B2 and B3 scenarios measures the effect of a lower failure probability due to the dike reinforcement. Similarly, the climate change effect is measured by comparing losses under B1 and B3 scenarios (Figure 7).[23]

Figure 7. Impact of Climate Changes and Adaptation in the Embanked Area

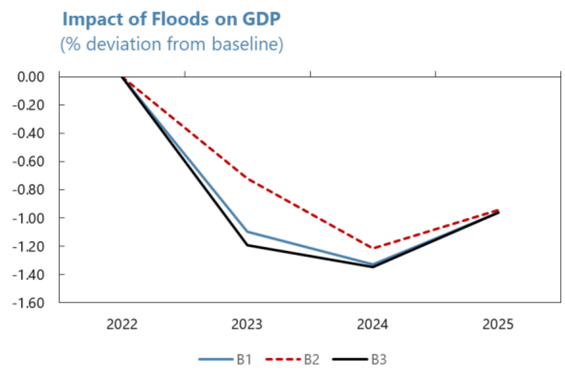
[23] According to Table 4, these scenarios assume 4 simultaneous breaches. As the B2 scenario involves different hydraulic loads, the breach locations differ from B1 and B3, contributing to more pronounced house price shocks.

The reinforcement of flood defenses reduces physical capital damage from floods.

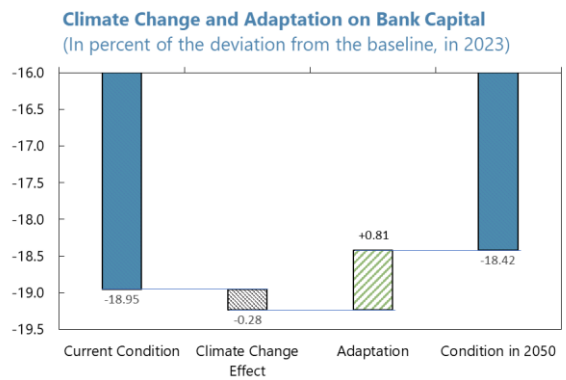
Capital and House Price Shock by Scenario

Return Period: 10,000 years				
Scenario			Capital Shock	House Price Shock
	Climate	Failure Probability		
B1	Current	Current	0.200	9.6
B2	2050(W+)	2050	0.062	10.5
B3	2050(W+)	Current	0.241	9.5

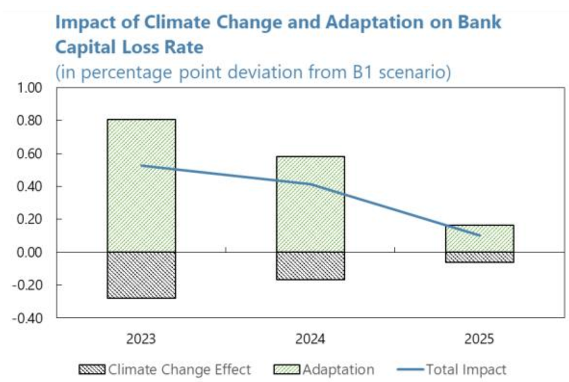
The adaptation plan serves as an absorber of the adverse impact on the economy.



Climate changes and the adaptation plan have the opposite impacts on bank capital loss.



Lower probability of defense failure mitigates bank credit risks.



While climate change events have negative impacts on the bank capital, the government's current reinforcement plan is strong enough to absorb the capital losses from climate changes. A 1-in-10,000-year flood in Region II under the current conditions generates 0.2 percent destruction in capital stocks. Despite higher hydraulic loads, the damage rate is expected to decrease by 0.138 percentage point under the conditions in 2050, thanks to the dike reinforcements. In the B1 scenario, bank capital losses increase by 18.95 percent relative to losses in the baseline in 2023. While higher hydraulic loads add losses of 0.28 percentage points (the climate change effect in the B3 scenario), the lower defense failure probability in 2050 absorbs the losses by 0.81 percentage points (the adaptation effect), leading to lower the capital loss rate by 0.53 percentage point in total under the B2 scenario.

7.3 Impact of extreme flood scenarios

The extreme scenarios (EDO scenarios) consider exceptionally rare flood cases, assuming simultaneous breaches of multiple dikes in the region. In the coastal storm surges scenarios in both Southwest and central coast area (Region I) and Wadden sea area (Region II), the dike breaches also cause a devastating surge on the lake districts. These two scenarios impact the widest area approximately 4,300 km^2 and 4,600 km^2, respectively, which adds up to nearly 26 percent of total land area in the Netherlands. However, the damage is significantly greater in the Region I due to its denser population, leading to substantial decline in GDP. On the other hand, despite a smaller inundated area, the flood water depths in Rhine and Meuses (Region III) and Lower river courses (Region IV) area are higher than other regions on average. (Figure A-1)

In all extreme flood scenarios, a severe flood can cause a small, but nonnegligible capital ratio reduction in the first year (Figure 8). The bank capital ratio drops by 0.3-0.6 percentage points relative to the baseline, standing above the requirement. While the reduction in GDP is larger in EDO-I scenario than in other scenarios, the magnitude of reduction in the capital ratio is not as large as the difference in GDP reductions. This can be attributed to three main factors: first, the significant heterogeneity in the size of the impact across banks; second, our probability of default (PD) model for the Netherlands suggests a relatively small impact of GDP changes on future PD trajectories; and lastly, the absence of other risk channels (e.g., interest risk and market risk) in this analysis.

An additional sensitivity analysis with higher house price shocks adds 0.1 percentage point decline in the bank capital ratio. In this case, the loss rate in house value due to regional flood applies to the national-wide house value in the Netherlands, without consideration of the elasticity of regional price to overall house price. Higher house price shock amplifies the adverse impact on the capital ratio, especially in the first year.

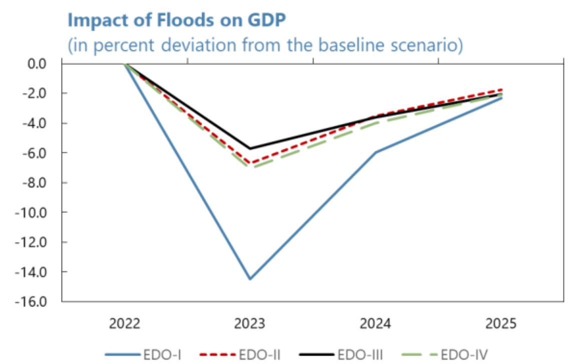
Figure 8. Impact of Extreme Flood Scenarios

The extreme flood scenarios have negative impacts on the capital stock and house prices…

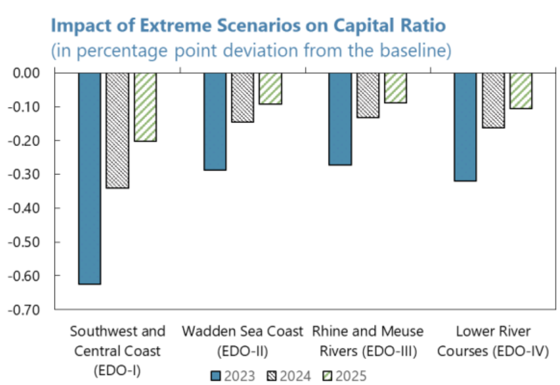
Capital and House Price Shock by Scenario

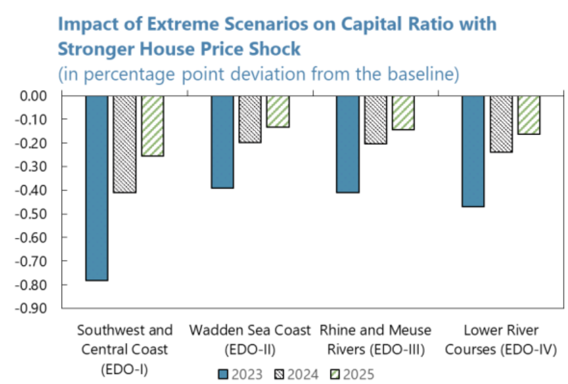
Scenario	Capital Shock	House Price Shock
EDO-I	5.4	13.9
EDO-II	2.4	13.9
EDO-III	1.9	17.7
EDO-IV	2.4	17.4

… and GDP, especially in Region I.



Severe floods can cause small but non negligible capital ratio reductions.





7.4 Impact of floods in the neighboring countries

In July 2021, heavy rains across Belgium, Germany, the Netherlands, and many other western European countries, caused streams and rivers to overflow their banks in many locations. Some of the affected regions experienced rainfall of this magnitude not seen in the last 1,000 years.[24] The floods are estimated to have caused a minimum of 10 billion euros in total damage, with particularly severe damage to infrastructure in Belgium and Germany.[25] According to the international disaster database (EM-DAT), the damage per GDP in Germany was approximately three times larger than that in Belgium.

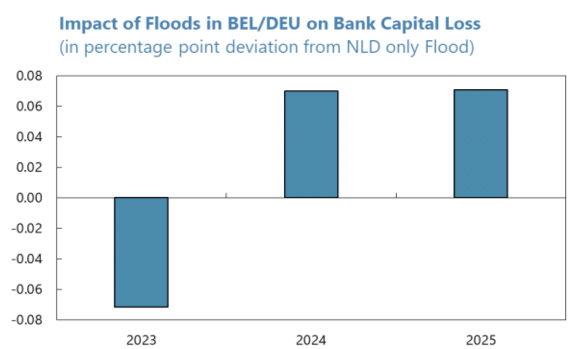
Floods along Rhine and Meuse River area in Germany and Belgium have minimal spillover impacts to Dutch banks despite theirs exposure to those countries. On average, of the total exposures of the Dutch banks in our sample, 7.6% is in Germany and 5.8% in Belgium.[26] Damage rates, or capital shocks, of Germany and Belgium are selected based on the evidence from the 2021 flood event. While floods in the neighboring countries have negative impacts to banks' capital in the first year, the impact is very small, increasing the capital loss rate only by 0.06 percentage point relative to the scenario with floods only in the Netherlands based on the scenario for region III and 1-in-100 year return period (Figure 9). The impacts of floods on Germany and Belgium are not large enough to transmit additional credit risks to Dutch banks. However, we note that the flood scenarios for Germany and Belgium were based on less granular data. Adopting more granular flood and collateral data from Germany and Belgium would help refining the assessment of damage and spillover impacts on the banks.

Figure 9. Impact of Floods in the Neighboring Countries

Floods from the neighboring countries adds bank capital losses, but with limited impacts.

Capital and House Price Shock by Scenario

Return Period: 100 years		
Scenario	Capital Shock	House Price Shock
NLD	0.124	10.5
DEU	0.041	-
BEL	0.13	-



[24] https://www.nytimes.com/2021/07/16/world/europe/germany-floods-climate-change.html

[25] https://www.wsj.com/articles/germany-flooding-bernd-whats-happening-11626446298

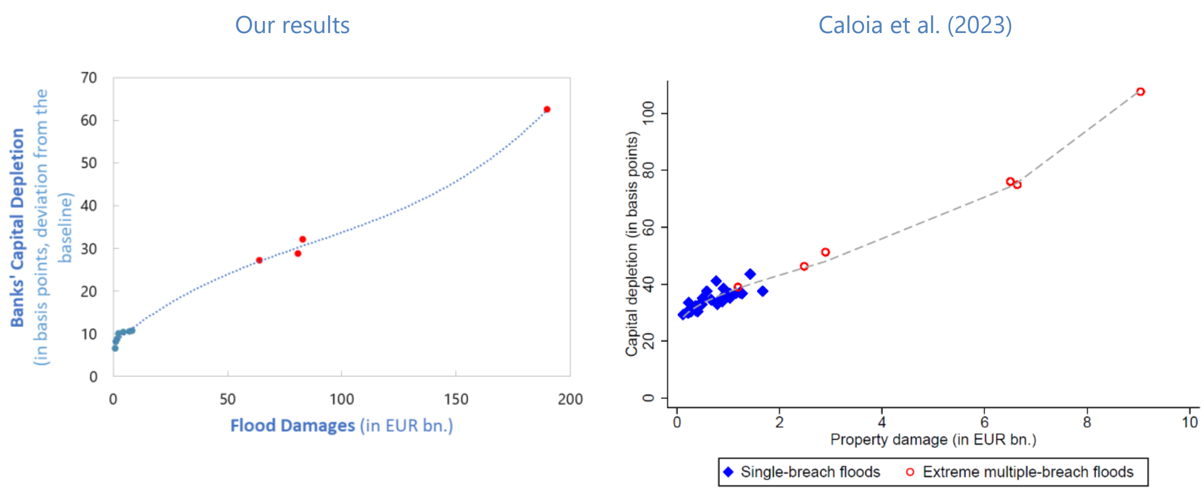
[26] For confidentiality reasons, these numbers are based on end 2020 data from the 2021 EBA Stress Test.

8. Discussion

Overall, our results show that climate physical risks from floods have modest impacts on the Dutch banking sector. The local nature of floods limits the overall damage to physical capital (e.g., buildings, infrastructure) compared to the total capital stock of the country. However, in the most extreme flood scenario, a severe flood can still cause a nonnegligible bank capital ratio reduction in the first year. Looking at all results together, similar to the results in Caloia et al. (2023) reported in Figure 10 below, we also find a non-linear relationship between flood damages and banks' capital depletion. For ease of comparability, we report flood damage from each scenario in EUR bn and banks' capital depletion as a deviation from the baseline in basis points. We note that the flood damages estimated in our study are much larger than the ones in Caloia et al. (2023), as they focus only on buildings that serve as collateral for banks' loans. By contrast, we estimate damages for a broader set of economic exposures, namely all businesses, residential, infrastructure, as well as others, in the affected regions (see Table 4). Non-linearity is particularly pronounced for the most damaging EDO scenario. This highlights the importance of considering extreme, although still credible, scenarios as the impact on the banking sector could be much more pronounced.

Figure 10. Flood Damages and Impact on Bank Capital

There is a non-linear relationship between flood damages and the impacts on bank capital.



Note: The dashed trend line in the left chart represents an estimated polynomial of degree 3. The red dots in both charts represent EDO scenarios.
Source (RHS figure): Caloia et al. (2023).

Most importantly, our results show the importance of adaptation measures to mitigate the impact of climate change. Although the impact of floods on the banking sector is limited, climate change can intensify the losses from floods, putting downward pressure on capital ratios. Our comparative analysis of current and future climate conditions and different dikes' failure probabilities for the type B floods suggests that the Dutch government's current reinforcement plan, which encompasses measures to strengthen dikes and enhance flood warning systems, could help mitigate some of the anticipated losses from climate change.

While we focus on banking sector aggregate results, these results mask heterogeneity across banks and vulnerabilities at the individual borrower level. Due to the lack of access to loan-level data, we cannot link the estimated flood damages on individual buildings to banks' geolocational exposures. We compared our results with the ones from the flood risk analysis on the Dutch banking sector in Caloia et al. (2023), which takes this approach. Under the same extreme EDO scenarios, they estimate a capital depletion between 40 and 110 basis points (see Figure 10). Our estimates are in a broadly comparable range, although smaller. The most damaging scenario, EDO-I, which considers a major multiple-breach event leading to flooding of most of the western part of the Netherlands leads to a capital depletion of close to 110 basis points for Caloia et al. (2023). This is almost double our estimate for the same scenario. Thus, abstracting from floods' impact at the borrower level can lead to underestimating flood risks for the banking sector.

Given the uncertainty associated with the scenarios and models, the analysis and results should be interpreted with caution. In terms of the flood scenarios, as discussed above, we note that expert judgment was used to incorporate the impact of future climate. Flood scenarios designed with detailed flood maps under future climate conditions would provide a more accurate assessment of both climate change impact and adaptation. Further, when considering floods in neighboring countries, we need to rely on a different set of less detailed data. The analysis of the impact of floods in Belgium and Germany could be improved with more specific flood information and exposure data from these countries. We also only focus on one natural hazard, ignoring the compound impact with other important hazards, such as droughts, which could lead to larger financial stability risks. The banking sector stress test model is also subject to various simplifying assumptions due to the constraints in data and the model's scope. In particular, this analysis focuses on the macroeconomic impact of floods using scenarios which incorporate floods' damages. Although the damage rates from flood scenarios are estimated based on flood risks in year 2050 or 2100, the damages are assumed to materialize within the short horizon of 3 years. We also only consider the credit risk channel, ignoring other channels of propagation of climate risks, and assume that banks' balance sheet stays constant over the scenario horizon A more comprehensive examination is needed to understand the complete set of impacts of floods through alternative channels to banks.

9. Conclusions

We developed a physical risk stress testing framework focused on estimating the credit risk impact of flood scenarios on the Dutch banking sector. Flood scenarios and their damages were carefully designed in collaboration with Dutch climate experts to leverage the granular geographical data on flood water depth and their methodology for damage estimation. Flood scenarios focused on flood-prone areas based on different threats (sea, rivers, lakes) and susceptibility to the largest damage due to higher population and economic activity. Our flood scenarios consider a large number of characteristics, including geographical regions, flood types, climate conditions, return periods, and most importantly flood protections.

We are among the first to explicitly consider the impact of adaptation measures on floods under future climate conditions. Our results show the importance of considering the heterogeneous characteristics of floods, including adaptation. We find that adaptation can significantly mitigate the capital impact on banks. We also find non-linear relationships between flood damages and banks' capital depletion, highlighting the importance of considering extreme scenarios.

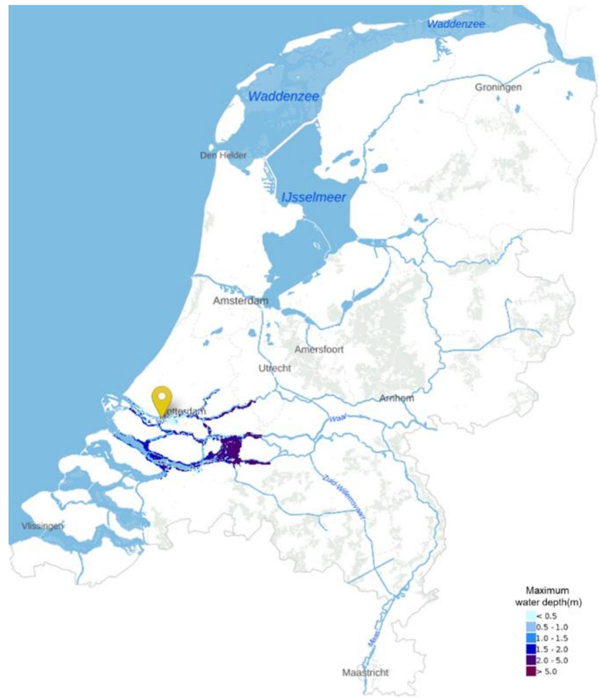
This framework could be improved and extended in several directions. For example, it should include more detailed climate change scenarios and additional natural hazards. Most importantly, given the highly localized nature of floods, obtaining geolocated banks' loan level data and linking flood damages to loans' collateral would be desirable. However, in the absence of this confidential information, our framework provides a valuable approach to estimating financial stability risks from floods. Given that many countries face data constraints, due to data gaps on geolocated exposures in the financial sector, we hope our framework can provide them with a useful tool for climate physical risk analysis.

Annex I: Flood Maps of Scenarios

Figure A-1. Flood Maps of Unembanked Area (Region IV)

Scenario A1 – Current Climate Condition

Scenario A3 – Climate Condition in 2100 (2100W+)



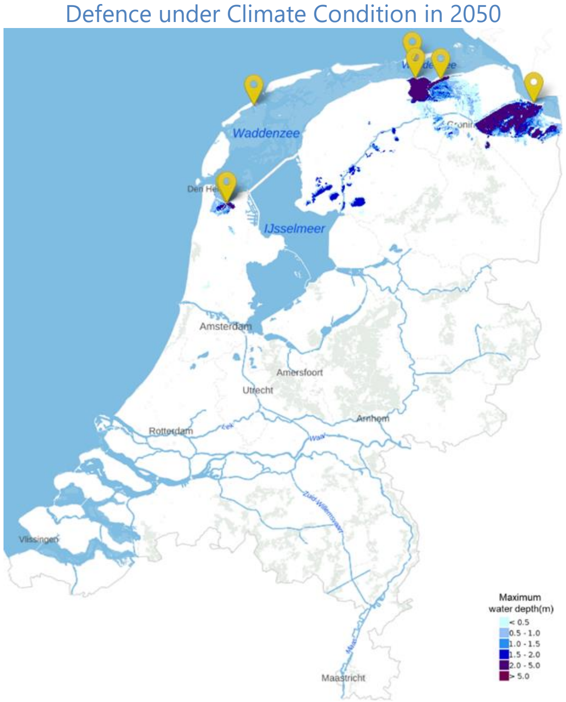
Note: The yellow flags in the maps indicate the location of the water overflow. The damage from scenario A2 under climate conditions in 2050 (2050W+) is calculated by taking the average of the damages from scenarios A1 and A3. The return periods of the scenarios are 1,000 years.
Source: LIWO

Figure A-2. Flood Maps of Embanked Area

Scenario B1 (Region II) – Current Failure Proability of Flood Defence under Current Climate Condition

Scenario B2 (Region II) –Failure Proability of Flood Defence in 2050 under Climate Condition in 2050

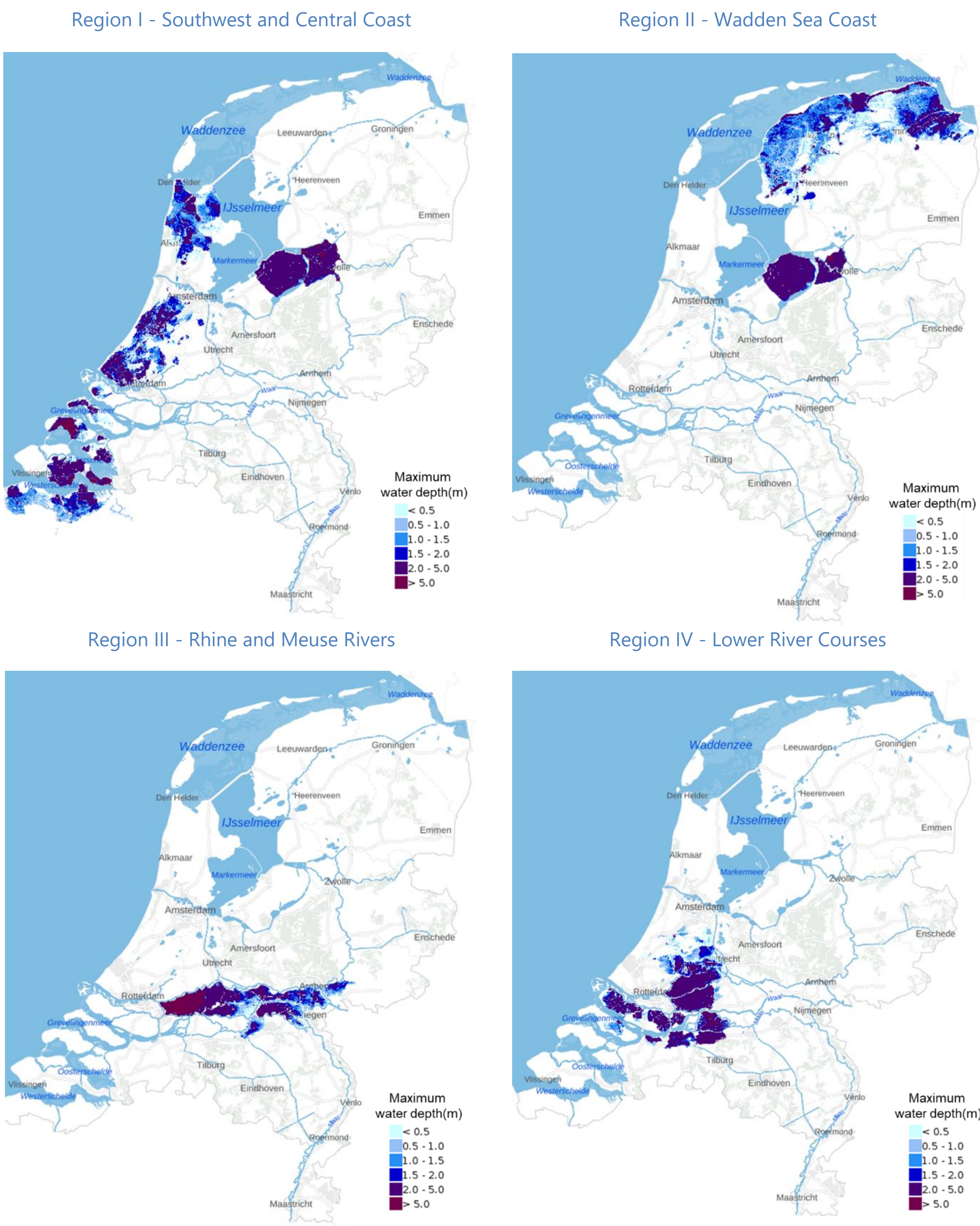
Scenario B3 (Region II) – Current Proability of Flood Defence under Climate Condition in 2050



Scenario B3 (Region III) – Current Proability of Flood Defence under Climate Condition in 2050

Note: The yellow flags in the maps indicate the location of breaches in the flood defence system. The return periods of the scenarios are 10,000 years, except for the scenario in Region III which assumes the return period of 100 years.
Source: LIWO

Figure A-3. Flood Map of EDO Scenarios



Source: LIWO

Annex II: Capital and House Price Shocks under Flood Scenarios

Table A-1. Region I - Capital and House Price Shocks (in percent)

Capital Shocks	Scenario Name	Climate Condition	Failure Probability	Return Period			
				10	100	1000	10000
Unembanked Area	A1	Current	-	0.001	0.002	0.006	0.020
	A2	2050 (W+)	-	0.002	0.004	0.013	-
	A3	2100 (W+)	-	0.002	0.006	0.020	-
Embanked Area	B1	Current	Current	-	-	0.025	0.053
	B2	2050 (W+)	2050	-	-	0.032	0.047
	B3	2050 (W+)	Current	-	-	0.028	0.065

House Price Shocks	Scenario Name	Climate Condition	Failure Probability	Return Period			
				10	100	1000	10000
Unembanked Area	A1	Current	-	1.46	2.84	2.69	3.55
	A2	2050 (W+)	-	2.15	2.77	3.12	-
	A3	2100 (W+)	-	2.84	2.69	3.55	-
Embanked Area	B1	Current	Current	-	-	17.4	13.8
	B2	2050 (W+)	2050	-	-	8.9	6.7
	B3	2050 (W+)	Current	-	-	17.0	15.8

Note: The return period of EDO scenario is larger than 10000 years.

Table A-2. Region II - Capital and House Price Shocks (in percent)

Capital Shocks	Scenario Name	Climate Condition	Failure Probability	Return Period			
				10	100	1000	10000
Unembanked Area	A1	Current	-	0.001	0.003	0.006	0.012
	A2	2050 (W+)	-	0.002	0.004	0.009	-
	A3	2100 (W+)	-	0.003	0.006	0.012	-
Embanked Area	B1	Current	Current	-	-	0.032	0.200
	B2	2050 (W+)	2050	-	-	0.024	0.062
	B3	2050 (W+)	Current	-	-	0.035	0.241

House Price Shocks	Scenario Name	Climate Condition	Failure Probability	Return Period			
				10	100	1000	10000
Unembanked Area	A1	Current	-	12.00	10.96	7.49	8.48
	A2	2050 (W+)	-	11.48	9.22	7.99	-
	A3	2100 (W+)	-	10.96	7.49	8.48	-
Embanked Area	B1	Current	Current	-	-	8.9	9.6
	B2	2050 (W+)	2050	-	-	10.3	10.5
	B3	2050 (W+)	Current	-	-	9.0	9.5

Note: The return period of EDO scenario is larger than 10000 years.

Table A-3. Region III - Capital and House Price Shocks (in percent)							
Capital Shocks	Scenario Name	Climate Condition	Failure Probability	Return Period			
				10	100	1000	10000
Unembanked Area	A1	Current	-	0.009	0.012	0.025	0.024
	A2	2050 (W+)	-	0.011	0.019	0.030	0.040
	A3	2100 (W+)	-	0.012	0.025	0.032	0.043
Embanked Area	B1	Current	Current	-	0.029	0.150	0.912
	B2	2050 (W+)	2050	-	0.000	0.200	0.529
	B3	2050 (W+)	Current	-	0.124	0.150	0.912
House Price Shocks	Scenario Name	Climate Condition	Failure Probability	Return Period			
				10	100	1000	10000
Unembanked Area	A1	Current	-	24.71	21.97	17.94	7.43
	A2	2050 (W+)	-	23.69	16.97	16.20	16.56
	A3	2100 (W+)	-	21.97	17.94	7.43	21.38
Embanked Area	B1	Current	Current	-	7.9	9.7	7.9
	B2	2050 (W+)	2050	-	16.6	14.4	13.6
	B3	2050 (W+)	Current	-	10.5	11.1	7.9

Note: The return period of EDO scenario is larger than 10000 years.

Table A-4. Region IV - Capital and House Price Shocks (in percent)							
Capital Shocks	Scenario Name	Climate Condition	Failure Probability	Return Period			
				10	100	1000	10000
Unembanked Area	A1	Current	-	0.005	0.008	0.020	0.044
	A2	2050 (W+)	-	0.007	0.014	0.032	
	A3	2100 (W+)	-	0.008	0.020	0.044	
Embanked Area	B1	Current	Current	-	0.003	0.353	0.353
	B2	2050 (W+)	2050	-	0.001	0.001	0.001
	B3	2050 (W+)	Current	-	0.002	0.353	0.382
House Price Shocks	Scenario Name	Climate Condition	Failure Probability	Return Period			
				10	100	1000	10000
Unembanked Area	A1	Current	-	0.91	0.57	1.26	1.70
	A2	2050 (W+)	-	0.74	0.92	1.48	-
	A3	2100 (W+)	-	0.57	1.26	1.70	-
Embanked Area	B1	Current	Current	-	2.7	15.7	15.6
	B2	2050 (W+)	2050	-	4.0	4.1	5.1
	B3	2050 (W+)	Current	-	3.7	15.6	15.5

Note: The return period of EDO scenario is larger than 10000 years.

Annex III: PD Trajectories of Mortgage Portfolio

Figure A-4. PD Trajectories of NDL Mortgage Portfolio

Note: The charts report the estimated system-wide PDs under the baseline and flood scenarios.

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