NATURANCE

Nature for insurance, insurance for nature

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Deliverable 4.2: Improved methods for the assessment of risk reduction achieved by NBS for insurance and for assessing co-benefits to society (M30) (VU)

WP4 – Evidence and methods

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Deliverable Title	Improved methods for the assessment of risk reduction achieved by NbS for insurance and for assessing co- benefits to society
Brief Description	In this deliverable, we highlight current challenges for assessing the benefits of NbS, both from a risk-reduction and a co-benefits perspective. We illustrate our improved metrics and methods through the case study of the European floods of 2021 that is co-developed with NATURANCE stakeholders.
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1. Executive Summary

The increase in frequency and severity of climate risk events highlights the need for investing in climate change mitigation and adaptation. To this end, nature-based solutions (NbS) could become an economically viable and effective alternative to traditional engineering solutions, as they provide co-benefits for society even in the absence of an adverse climate event. However, there are still several gaps and challenges when assessing the benefits of NbS, which can ultimately be a barrier to adoption. In this deliverable, we build upon a meta-analysis and systematic review, where several challenges in quantifying the risk-reduction benefits and co-benefits of NbS were identified.

There are still several challenges that can negatively impact the upscaling of investment in NbS, both for the public and the private sector. In this deliverable we explore these gaps both from the risk-reduction and the co-benefits (physical and economic) perspectives. Several limitations in deliverable 4.1. were identified regarding benefits assessment such as the limited amount of data and how some NbS are relatively recent. In this deliverable, we co-designed improved metrics and methods for assessing the risk-reduction and co-benefits of NbS with NATURANCE stakeholders in an Innovation Lab. The outcome of this co-design process was to focus this improved metrics and methods on NbS that reduce flood risk. Moreover, since NbS can take a longer time to fully realize their benefits, it may still be too early to draw definitive conclusions. From a risk reduction perspective, many existing assessments are conducted at a local scale, instead of catchment-wide evaluations, which are essential for understanding the full hydrological impact of NbS. Moreover, previous studies used a limited set of metrics to evaluate the risk reduction of NbS in physical units (e.g. changed hydrological conditions). For insurance companies and investors, it would be more useful to estimate monetary metrics, such as the reduction in annual expected losses from NbS. This is challenging because catastrophe models of natural disaster risk for insurance have historically not accounted for NbS, resulting in an underestimation of their risk-reduction potential.

The lack of co-benefits assessment would underestimate the total societal value of NbS when using cost-benefit analysis to compare with benefits of traditional engineered solutions. But co-benefit assessment also faces its own limitations and challenges. NbS co-benefits assessment has mostly focused on the positive aspects of NbS. However, NbS also provide certain “disbenefits”, such as vector-borne diseases, that should be included in the analysis and, in the case of our co-benefit assessment using a newly designed choice experiment, are included in the analysis for one of our attributes. This was also highlighted during the co-creation process of our new method by local stakeholders, leading to the inclusion of a land use change disbenefit category that would capture how much agricultural land would be converted into NbS. The social dimension of co-benefits also means that the design of assessment methods relies on knowing the challenges faced by local actors, increasing the importance of a co-creation approach. Lastly, the main challenge of co-benefit assessment is mostly about how to make these monetary results relevant for private sector stakeholders to increase funding in NbS projects that not only comes from the public sector.

Upon collaboration with NATURANCE stakeholders we decided to illustrate the new developments in methods for assessing the benefits of NbS using the European floods of the Summer of 2021 as our case study. This event showed that there is room for improvement when it comes to flood-risk management. The total economic damage, only in the Netherlands, amounted to 600 million Euros. Having the case study in mind, and to overcome the lack of involvement of stakeholders, we

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employed a co-creation approach that had two main components. The first was the "Innovation Labs", which consisted of three different focus groups to discuss the new methods that will later be applied in our case study. In the second session, we discussed current limitations of flood-risk modelling and the lack of evidence of the impact of NbS in flood-risk reduction with several stakeholders from the insurance industry. The last session with policymakers and local stakeholders from Limburg, the main impacted area in the Netherlands by the 2021 floods, was crucial for the design of the methods since policymakers described which NbS are being considered, ensuring that our modelling and choice experiment results will be relevant for flood-risk management in the region.

We developed a new object level catastrophe model with a coupled hydrological and NbS modelling approach at a detailed geographical scale to estimate the flood risk reduction of NbS. Our risk-reduction results show the impact of reforestation and water storage ponds in reducing damage from flooding since these were potential measures considered by the local authorities to limit flood risk. The scenario for reforestation assumes a 10% increase in forest area, whereas for retention ponds it consists of an enlargement of current ponds and creation of new ones upstream. Results show that NbS can indeed reduce flood risk for all the metrics used in the catastrophe model. However, reforestation seems to be much more cost-efficient than retention ponds with a benefit-cost ratio of 1.06. Reforestation can reduce damage with approximately 16 million Euros in a 1-in-25-year flood event. This positive impact also maintains for larger and less frequent floods. On the other hand, retention ponds show a 0.24 benefit-cost-ratio. Including co-benefits in the analysis can make a compelling argument for investing in this NbS.

To complement the risk-reduction results, we developed a new choice experiment and survey method that was conducted with over 2,000 respondents across the Netherlands. The objective was to understand preferences for different co-benefits of NbS and to deliver new metrics of the monetized co-benefits of NbS. In particular, the willingness-to-pay, through an increase in the waterboard tax, was estimated using the model results. These NbS would be developed in current agricultural land. One of the key findings of this stage was to see the responsibility allocation of flood adaptation, as a high percentage of respondents highlighted that the national government should be responsible for these policies instead of individual adaptation or private sector entities (e.g. insurers). They also selected "low-income households" as the group that would benefit the most from these policies. However, if we guide investments by the risk-reduction results, this may lead to NbS being in wealthier regions, where the monetary damage would be higher, leading to a lack of protection for these low-income households who may not have the means to adapt. Although our analysis is based on perceptions and subjective preferences, we highlight the importance of addressing this social dimension of risk in NbS investments.

The choice model results highlight the reluctancy of our respondents to give up agricultural land for NbS. The coefficient for conversion of agricultural land to NbS was negative and statistically significant. This is certainly valuable as a proxy for policy support. For example, reforestation has been shown to have a higher benefit-cost ratio, but it also requires more hectares to be converted, which may clash with the preferences of the local community. Other results of the mixed-logit model show a higher willingness to pay for reforestation and storage ponds over other NbS, such as wetlands and grassland.

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These results in this deliverable will contribute to the last deliverable D4.3 of Work Package 4, which focuses on designing NbS investment schemes for insurance, public and private sector. The risk-reduction benefits and the co-benefits will be combined in a social cost-benefit analysis, in order to make a comprehensive assessment of what the total economic value of these NbS would be. Moreover, D4.3 will estimate how much each actor, including the insurance sector, will benefit from implementing NbS. This is a key element for developing NbS financing strategies.

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1 Introduction

The increase in frequency and severity of climate risk events highlights the need for investing in climate change mitigation and adaptation (IPCC, 2021). At current trends, the number of climate-related disasters per year will increase from 400 in 2015 to approximately 560 by 2030 (The International Disaster Database, 2022). Extreme events, such as floods, heatwaves or wildfires, can have devastating effects on local communities if the appropriate measures to reduce risk are not adopted in advance. Economic losses stemming from natural hazards have reached an annual estimate of $150 - $200 billion in recent years, compared to $50 billion in 1980 (Munich Re, 2022). To this end, nature-based solutions (NbS) could become useful and effective in limiting climate risk. NbS are defined as “solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social, and economic benefits and help build resilience” (European Commission, 2019). NbS may mitigate natural hazards by mediating flow and nuisances, or through the maintenance of stable physical, chemical, and biological conditions.

The aim of this deliverable is to deliver improved metrics and methods for assessing the risk reduction potential and co-benefits of NbS. In order to do so, we build from the review that was conducted from the stock-taking exercise (available in NATURANCE Deliverable 4.1) and the different workshops (innovation labs) with key stakeholders from our case study region, where one session focused on risk-reduction methods and the other on co-benefit assessment. One key component is integrating NbS into natural disaster risk assessment models to provide more accurate estimates of potential damages from climate-related hazards and assess how NbS can mitigate such damages. The outcome will be a robust framework that not only improves risk-reduction assessments but also highlights the co-benefits of NbS, making them applicable for use in insurance models and enhancing their societal value. This will provide more comprehensive tools for evaluating both the direct and indirect benefits of NbS, supporting decision-makers in implementing effective and sustainable solutions.

The stock-taking that was conducted as part of the D4.1 deliverable of NATURANCE showed that the risk-reduction and co-benefits of NbS are context-specific. A knowledge gap exists in understanding their metrics in specific case study contexts. Hence, the development of new methods and metrics for these assessments is best illustrated in a case study context. In this case, these improvements will be illustrated using the case study of Limburg. Limburg was the region of the Netherlands which was the most impacted by the European floods of 2021. In the summer of 2021, an episode of extreme precipitation caused devastating flash floods in several European countries, including the Netherlands, the United Kingdom, Germany, Belgium and Luxemburg. Several thousands of people had to be evacuated from their homes. The human losses were devastating: 243 died because of the floods (Deltares, 2021). In terms of assets, it is estimated that, only in the Netherlands, monetary losses amounted to 350 - 600 million euros. This highlighted the need for improving the risk management system in place with new adaptation solutions. In this context, several NbS have been planned (or already implemented) by local authorities. However, the full set of benefits of NbS is unclear, which limits further investments. Hence, in consultation with NATURANCE stakeholders we choose the Limburg region, a high-risk area in the Netherlands that was severely impacted by the 2021 floods, as the focus of our case study and Innovation Labs. These Innovation Lab sessions focused on co-designing the new metrics and methods included in

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this deliverable together with stakeholders from the insurance and public sectors. We presented a new object-based model, which accounts for NbS, to insurers and discuss how this could impact premiums. This could improve insurability and reduce the insurance gap discussed above. This could be seen as a redistributive policy. Additionally, we discuss with local stakeholders in Limburg which co-benefits they believe to be more important, based on the NbS already in place in the Limburg region.

This deliverable will be structured as follows. Section 2 delves into the co-creation process with the stakeholders in the different Innovation Lab Sessions. Section 3 illustrates the improvements in risk modelling and the case study implementation, will be introduced. Lastly, sections 4 and 5 focus on the co-benefits of NbS. Section 6 assesses the ecosystem services provided by NbS for climate risk, whereas Section 7 delves into the monetization of co-benefits. Section 8 provides a conclusion and provide suggestions for further research.

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2 Co-design process with stakeholders for improved metrics and methods for assessing NbS

Co-designing is the process by which the design of a particular methodology is not only carried out by the researcher alone, who may be detached from needs from affected communities or the private sector and instead involves a cooperation exercise between the stakeholders since their goals align. Co-designing improved methods allows us to solve several barriers previously identified. D4.1 showed that many of the current methods assessing the risk-reduction and co-benefits are not directly useful for societal stakeholders, such as insurance companies and policy makers involved in the creation of NbS. An example of this is the lack of inclusion of NbS in flood-risk modelling, which increases the difficulty of the role of insurers to adjust the premiums after NbS for flood-risk reduction have been implemented. Additionally, the co-benefits assessment is difficult to complete without talking to local governments to understand which NbS are being considered and which problems associated with NbS implementation we can encounter in the area. For example, stakeholder input allowed us to include land use variables in the new choice experiment that we designed to estimate NbS co-benefits as it was mentioned as a key issue for our case study area the Limburg province. We overcome this issue by co-designing these methods together with key stakeholders early in the research process.

Work Package 2 addresses the co-creation problem and tries to connect academia, public and private sectors together. In the first round of NATURANCE workshops, before this deliverable was finished, three different innovation labs (IL) were conducted. Innovation Labs are safe spaces that that offer a collaborative environment where different agents are joined together for the purpose of innovating and generating new solutions. The NATURANCE ILs bring together many different types of actors and knowledge, fostering experimentation and experiential social learning. The three ILs of the first cohort focused on the following topics:

1. **Improving metrics for risk reduction benefits and co-benefits of NbS.** This IL was led by the VU and took place in three separate sessions between November 2023 and March 2024. The results and feedback gathered in this IL were the basis to produce this deliverable, as it was explicitly design with this goal in mind and we were able to discuss and their limitations with the chosen methods with the relevant stakeholders. This will be discussed in detail below.

2. **Investing in natural flood management in urban areas in the UK.** This IL was led by London School of Economics. This IL started in June 2023 and the last session took place in May 2024. This lab aimed to co-develop business cases with relevant stakeholders to enable insurers to unlock both direct and indirect investments in natural flood management (NFM) in urban areas across the UK.

3. **Harnessing insurance to promote nature-based solutions for wildfire risk management.** The third IL was led by IAASA and was conducted between June 2023 and May 2024. this lab explored how insurance can promote NbS for wildfire risk management (WFRM). It facilitated discussions among insurers, risk managers, ecologists, and other stakeholders to develop innovative insurance products that encourage NbS adoption.

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The VU-led IL was the starting point to improve the assessment of risk-reduction benefits and co-benefits of NbS in a case study with a recent flood event: the 2021 floods in Limburg. Flood risk in the Netherlands has been a growing concern, exacerbated by climate change and the resulting extreme weather events. By connecting the academic research community with insurance industry representatives, policymakers, and local government officials, this Innovation Lab aimed to align theoretical knowledge with practical applications, addressing societal demands for NbS for flood risk reduction. This Innovation Lab facilitated a multidisciplinary dialogue aimed at enhancing methods for assessing the flood risk-reduction potential and co-benefits of NbS in the Netherlands. The first session served as an introduction to the Lab, the second focused on catastrophe modelling and risk reduction, and the third session served as a focus group on co-benefit assessments. Across the three sessions, the Lab brought together over 60 experts from the Institute for Environmental Studies (IVM), Rijkswaterstaat, the Municipality of Valkenburg aan de Geul, the Dutch Association of Insurers, and other key organizations to exchange knowledge and collaboratively improvements to current methods to assess NbS.

This lab served as a collaborative platform, integrating insights from the academic, insurance, and governmental sectors to improve flood-risk assessment models and non-market valuation methods in order to explore NbS's financial viability. The objective is to improve methods to assess the benefits of NbS applying the feedback received from our stakeholders. On the one hand, insurers highlighted that the current models developed at IVM, which include the impact of NbS, are new for them and could potentially impact premiums or insurability, if there is empirical evidence that NbS reduces flood risk. On the other hand, local governments are concerned about land use changes and believe that the disbenefits of land use change should be taken into account when considering investment in NbS.

The second session of the VU-IVM Innovation Lab focused on improving methods to assess the risk-reduction potential of NbS. It aimed to combine the academic in-house expertise of flood-risk modelling at the IVM with insights from stakeholders in the insurance sector. The main goal was to obtain a better understanding of the views of insurers regarding NbS risk assessment and financing. A new hydrological model was introduced to stakeholders, which will be used in conjunction with a flood damage and an insurance model to estimate the impact of NbS for insurers. The session also provided a platform for discussion about how insurance can utilize these outputs and what additional information would be relevant in order to mainstream NbS financing.

At the beginning of the session, IVM researchers presented the latest advancements in in-house flood-risk modelling and its application in insurance modelling to estimate the effects of NbS on insurance affordability and premiums. This session of the lab, as well as the following one on co-benefits, focused on the 2021 Limburg flooding case study. In the summer of 2021, extreme precipitation provoked devastating flood across several European countries. Our private sector stakeholders highlighted that all proposed innovations by IVM modelers are new for insurers. Modelling is usually purchased from a third party, and it is a “black box” at times. The new proposed methodology would also help the case for NbS since a better understanding of their benefits could also impact premiums and affordability in areas where they are implemented as long as they prove to be effective. Another suggestion to improve modelling from the insurers (ASR) was to include household adaptation measures in flood risk assessments. This could also motivate insurers to offer discounts to those households that lower their risk by taking adaptive measures. The proposed

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object-based approach for assessing flood risk reduction from NBS was also interesting for the insurers. The insurers were asked whether we could expect a change in premiums reflecting the lower risk due to NbS. The response was that property markets are sufficiently competitive so risk-reduction should in principle be reflected by a lower premium. The consensus by insurers was that the government should be taking the lead in investing in risk-reduction measures. The one-year insurance contracts create a free-rider problem in the competitive insurance market: one insurer can pay for an NBS, but if the household changes insurers in the following year, they will not enjoy the benefits.

The third session focused on improving methods to assess the co-benefits (and disbenefits of NBS). This is extremely important in order to conduct a comprehensive assessment of NBS, which can then inform investment decisions. At the beginning of the session, the choice experiment that is planned for Limburg was introduced so all participants were aware of how the input they provided would feed into research for NATURANCE. The stakeholders highlighted that, even if there are already discussions in place to implement NbS in Limburg, they are still considering what could be the optimal solution. These discussions influenced the choice of the different NbS to be included in the alternatives for our choice experiment. Another challenge identified by stakeholders was the concern regarding land use changes (spatial constraints) and the role of private/public land ownership in the decision-making process. It was also highlighted in the systematic literature review (D4.1), there is a lack of disbenefits analysis. In this case, since the stakeholders considered it the main concern in a country such as the Netherlands, we will include loss of agricultural land as part of the trade-off in the choice cards that will be shown to respondents in our newly designed choice experiment method for valuing co-benefits of NbS. Some limitations found in the stock-taking phase should be addressed in future research. For example, 66% of the papers included in the meta-analysis were based on studies conducted in the Global North.

In summary, the process of co-designing the improved methods and metrics for this deliverable allowed us to solve some of the methodological issues identified before, such as:

Table 2.1. Co-creation process and Innovation Labs

Challenge / gap identified in stock-taking phase	Why is this an issue for a comprehensive assessment of NbS?	How was it addressed through co-creation
Catastrophe models of climate risk do not tend to include NbS impact	This can lead to an underestimation of the impact of planned NbS and current nature that is limiting the impact of climate risk.	In the second session of the IL, we discussed with insurers and modelers the object-based catastrophe model developed at IVM. The feedback from insurers helped to understand how this model can impact premiums, due to the competitive market in the Netherlands.
Decision-making based solely on risk-reduction of NbS ignores the societal value they provide through co-benefits	The lack of co-benefits assessment would underestimate the total societal value of NbS when using cost-benefit analysis to compare with benefits of traditional engineered solutions.	We combine the risk-reduction assessment with a choice experiment that indicates the value respondents place on different co-benefits of NbS.
NbS co-benefit assessments ignore disservices	Not including disservices can distort the real value of NbS, leading to overestimation.	Local stakeholders from the region of Limburg were consulted about what the main disadvantages with implementing several NbS to

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	Disservices, such as mosquitoes or land use constraints, could be impactful in respondents' valuation of NbS co-benefits.	reduce flood risk in the Limburg region could be. They mention that the intensive use of agriculture could be seen as an issue by locals, as the NBS would have to be developed on agricultural land. Hence, we included land use considerations in our choice experiment. Some other potential disbenefits were not deemed as relevant for the Limburg region.
Lack of primary data	NBS co-benefits assessment is case-specific so local data/modelling is needed to inform policymaking	Collecting local survey data for a region that was recently hit by a flood and that is currently planning NbS for flood-risk reduction is an opportunity for a case study to test our improved methods to assess co-benefits and risk-reduction benefits. The results will be specific to the region and will be valuable for policymakers, but also lessons learnt could be applied in the international context.
Lack of collaboration with local actors in assessment of NbS benefits	Design of methods for co-benefits rely on knowing the challenges faced by local actors, such as land use constraints for NbS development	As mentioned above, the local government in Limburg informed us of the NbS planned for the region. This was used as the different alternatives of the choice experiment. The levels of the ecological improvements were decided after consulting with experts from KIT.

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3 Risk-reduction assessment of NbS

Policymakers aiming to reduce flood risk face a complex task of evaluating costs and benefits of a (potentially) wide range of options. There are several notable barriers that limit the uptake of NbS compared to grey Disaster Risk Reduction (DRR)-solutions (as reviewed in NATURANCE D3.1), of which an important one is the lack of robustness concerning the DRR of NbS. Costs and benefits for engineered DRR-solutions can be estimated in a straightforward and reliable manner, largely because there is considerable experience with this type of flood adaptation, but also because these measures are specifically designed to reduce flood risk. Although there are various NbS that also reduce flood risk, their effectiveness at doing so is often more complex and uncertain to establish. This is partly because the evidence-base is lower, particularly concerning the large-scale implementation that is often required for NbS to become an effective strategy (Opperman & Galloway, 2022). But it is also because NbS have more complex hydrological and hydrodynamic impacts compared to many engineered DRR-solutions (Guido et al., 2023).

The higher perceived uncertainty concerning the flood risk reduction quality of NbS causes such DRR-measures to have a lower priority compared to more established engineered DRR-measures in decision-making processes (Opperman & Galloway, 2022). Often when a NbS is applied to reduce flood risk, it is combined with a dike or levee to guarantee effectiveness. Mainstreaming NbS as a flood DRR-strategy, therefore, requires improvements in flood simulation tools that account for the hydrological and hydrodynamic effects of NbS, and that allow the flood risk reduction of specific NbS to be captured.

Flood risk simulations are a useful tool for flood risk management to evaluate different DRR-options. Such simulations are often designed to follow the established method of assessing flood risk, which is by combining the elements of hazard, exposure, and vulnerability (Kron et al., 2005). Flood hazard captures the biophysical aspect of flooding, including the meteorological and geological conditions that cause water levels to exceed the embankments of a river and inundate land. Exposure measures the people and assets (and their values) that are located on the potentially inundated land. Vulnerability captures the extent to which exposed assets are damaged by inundation.

There are many different DRR-options available to policymakers, many of which affect one of the three described elements of flood risk modeling. Dikes, levees, and many types of NbS, including flood storage ponds, renaturalization of embankments, and reforestation of river catchments, affect flood hazard. Flood barriers (i.e., dikes and levees) prevent the inundation of land caused by a water-level that would exceed the natural embankments of a river. Many NbS are effective at reducing flood hazard by slowing down the runoff of water throughout a river's catchment, limiting the severity of peak river discharge. Besides limiting flood hazard, there are also FRM-strategies to limit flood risk by reducing exposure and vulnerability. For example, construction of new buildings may be prohibited in designated floodplains, and subsidies may be granted to flood-proof existing buildings (Aerts and Botzen, 2011).

In summary, the investment case for NbS is mostly public due to the public nature of NbS benefits, but partly NbS may be financed by private firms (insurers, banks, agricultural sector, etc.). Although not traditionally involved in DRR investments, insurers may play an important role in directly investing or increasing the attractiveness of NbS as a DRR-measure. In areas where flood risk is, or may become, uninsurable, due to excessive levels of flood risk, NbS may prove a valuable

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investment for insurers to increase their potential business. This may count especially in regions that are sparsely populated and where the costs of traditional grey DRR infrastructure can more easily outweigh the benefits. Besides directly investing in NbS, insurers may encourage investments in NbS by giving premium discounts equal to the amount of flood risk reduced by it. Such discounts may increase the interest by (local) governments to invest in NbS, which the government, for example, may fund through a tax increase equal to the reduced insurance premium.

For both ways that insurers may facilitate NbS investments, robust DRR metrics are required. Insurers need to know how much flood risk is reduced in order to set premiums that are financially sustainable. In practice, the integration of NBS in premium-setting by insurers is limited to several pilot projects (Uzsoki et al, 2021). Moreover, allowing (local) institutions to finance NBSs through insurance premium discounts requires insurers to estimate premiums on a sufficiently detailed geographical scale (henceforth this is referred to as "risk-based" premium-setting). In practice, also concerning this, the level of detail in assessing risk-based premiums for flood insurance is often limited.

In this chapter, we review the state-of-the-art in flood risk assessments, and the integration of NBSs in such assessments, which may be used by the insurance industry to set risk-based premiums. We consider limitations of existing assessment methods regarding their potential use to increase NBS investments, and we illustrate several innovations to address these limitations. To maintain a comprehensive overview of discussed methods, we structure the chapter based on the three components that determine flood risk, beginning with flood hazard, followed by exposure, and ending with vulnerability.

3.1 Hazard modelling

There are various established methods for assessing riverine flood hazard, each with associated benefits and shortcomings. The most advanced technique, one that estimates flood risk as a function of both severity and probability, is an integrated hydrologic-hydrodynamic approach. The hydrological simulation aims to assess the accumulation of water at a certain location in a river system. This process is often based on a probabilistic assessment of conditions that determine river runoff, including precipitation and water from melting snow and ice. For example, probabilistic hydrological models may estimate the river discharge triggered by conditions that are expected to occur once every 10, 100, and 1000 years.

Hydrodynamic simulations aim to capture how water moves downstream, and at which location the accumulation of river discharge causes a water-level to exceed natural or man-made embankments, triggering a flood. We discuss hydrologic and hydrodynamic simulation processes separately.

Hydrologic hazard simulations

Modeling riverine hydrology broadly involves two categories of input variables; one that assesses the origin of water ending up in a catchment, including precipitation, glacial meltwater, and groundwater; and one that captures geological features that determine the accumulation of water in a river, including steepness and roughness of terrain.

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The complex hydrological processes of water accumulating in rivers and streams can be simplified into several processes. All water in a river catchment originates from precipitation, but after it falls on land there are broadly four processes that affect where the water flows to. Some of the precipitation is intercepted by vegetation and other obstacles, preventing it from flowing downstream immediately after rainfall. Part of this intercepted rainfall never flows downstream, as it will evaporate at a later stage. Some of the rainfall ends up in surface depressions, including lakes, ponds, and small cavities in rock structures. Some of the rainfall infiltrates into the groundwater, part of which ends up recharging aquifer levels or in deep groundwater storage, but some of the infiltrated water ends up in the groundwater interflow that eventually joins the stream. All the rainfall that does not end up in either one of these processes will flow overland, directly joining the stream.

The amount of precipitation falling over a certain amount of time determines how the processes described above lead to the accumulation of water in a stream. The more precipitation falls in a given period of time, the more water cannot be infiltrated or held up by plants and obstacles, meaning more water ends up in streams through overland flow. Hydrological models aim to assess how much precipitation and how quickly this reaches a certain location in a river. In order to estimate flood risk at a later stage, hydrological models usually apply data on precipitation quantity and duration associated with multiple probabilities. Often, these precipitation intensity-duration-frequency relationships are based on local rainfall observations. For future assessments, relevant data can be obtained from global or regional circulation models, which apply assumptions on levels of greenhouse gas accumulation and global warming. Data on rainfall intensity-duration-frequency is often applied to fit a probability distribution, such as Gumbel's extreme value distribution, which allows the assessment of flood risk at a later stage.

Hydrological assessments can require substantially detailed geological and geographic data. Firstly, the direction and degree of slopes determine how rapidly precipitation can potentially end up in a stream through overland flow. Data for this assessment is often derived from Digital Elevation Models (DEM). Several globally available DEMs are based on satellite imagery and may reach a 30-meter resolution. Recent developments in LiDAR-technology, which is a remote-sensing technique that uses light detection, have enabled some regional DEMs to reach a resolution of 1 meter. Besides information on elevation, a hydrological model requires data on soil structures, to estimate infiltration, and vegetation, in order to assess the interception of overland flow. For this purpose, land cover maps are available, such as ESA's 10-meter resolution world cover map, which is also based on satellite imagery and remote-sensing techniques. Although these global datasets are useful for large-scale hydrological assessments, or for assessments in places where data availability is otherwise low, they do come with some limitations, particularly concerning location-specific geological and geographic information. Global land cover maps naturally have to maintain fairly broad categories on vegetation and soil types. A detailed local hydrological analysis may be improved by using information on vegetation and soil types found in a river's catchment.

Hydrodynamic hazard simulations

Hydrological simulations estimate water levels at given locations associated with certain probabilities of meteorological events occurring. At certain points, and under certain circumstances, water levels may exceed natural or man-made embankments, causing the inundation of land.

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Hydrodynamic simulations are designed to assess how excess river water inundates land, considering both the depth and velocity of water as it covers land.

Hydrodynamic models, sometimes called hydraulic models, are available in 1D or 2D variants. 1D hydrodynamic models essentially represent cross-sections of a floodplain in terms of altitude and potential obstacles for floodwater. After a floodplain is represented in many of these 1D maps, these models iteratively apply mathematical formulas that assess the depth and velocity of water entering the floodplain. The velocity of a flood is reduced by different obstacles, such as tree cover and buildings, which is often mathematically represented by Manning's n coefficient. Different landcover types have different effects on flood velocity, which is captured by different Manning's n coefficients (Kalyanapu et al, 2009).

2D hydrodynamic models apply the same mathematical principles to represent processes, but to a much more detailed extent, which is necessary because the 2D floodplain map includes many more possible directions for floodwater to flow than in a 1D map. As a result, 2D simulations are much more detailed than 1D models, although their complexity and computation requirements may pose limitations to their applicability. Both types of hydrodynamic models require similar input data, which includes elevation and landcover data. This data may be acquired from similar sources as was discussed regarding data requirements for hydrological modeling.

Modeling hazard adaptation

There are multiple ways to reduce flood hazard, either by preventing a flood from occurring, or by limiting the destructive power of a flood. The most common method applied to prevent the inundation of land by high river discharge is to heighten a river's embankments with dikes or levees. Higher embankments generally mean that at a given location, a certain rainfall event within the catchment is less likely to lead to flooding. Often, dikes and similar protection infrastructure are designed to withstand a chosen probability event, such as a 50- or 100-year event. Modeling the effectiveness of a dike within the coupled hydrologic-hydrodynamic framework is reasonably straightforward, as it can simply be integrated in the 1D or 2D representation of the floodplain. The effectiveness of a certain dike-height equals the inundation that would have occurred without it.

Besides raising embankments, described hydrologic and hydrodynamic processes show that there are many different ways in which the natural environment can contribute to reducing flood hazard. Vegetation within the catchment intercepts overland flow, thereby reducing the peak water-level in a river during or shortly after an intense rainfall event. This means that transforming man-made environments, such as farmland and pastures, to areas with more natural vegetation will reduce flood hazard. Moreover, water bodies and wetlands within the catchment are surface depressions that also limit overland flow, performing a similar function as increased vegetation within the catchment. Another NbS to reduce flood risk is the restoration of natural riverbeds. Often, rivers in inhabited areas are channelized and straightened in order to reduce the space that they take up. An issue with this development is that the peak water level as a result of a rainfall event rapidly moves downstream, potentially merging with high water levels from tributaries, and increasing the likelihood of a flood occurring. Natural riverbeds, which meander and have considerable vegetation, slow down the speed of water traveling downstream, reducing the probability that water accumulates to levels that cause a flood.

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The effectiveness of NbS to reduce flood risk can be assessed using the hydrologic-hydrodynamic modeling framework described earlier. For increased vegetation in the catchment, the effectiveness can be assessed by integrating a land-use scenario where currently man-made environment is replaced by certain types of vegetation. The effectiveness of vegetation to slow down overland flow is captured by Manning's n coefficient of roughness, which is established for several land use and vegetation categories (e.g., Mtamba et al., 2015; Van der Sande et al., 2003). The effectiveness of creating lakes, floodwater storage ponds, and the restauration of wetlands, at reducing flood risk can be assessed by integrating these as surface depressions or water storage areas in the water transportation map derived from the DEM. The effect of restoring riverbeds to their natural state is captured in the hydrological model by reducing the speed at which water can flow downstream.

1.

3.1.1 Limitations in current hazard modeling

Several studies have analyzed the effects of NbS on flood peaks, flood extent, and flood risk (e.g., Guido et al., 2023; Agarwal et al., 2024, Ruangpan et al., 2020; Ferreira et al., 2020). While these studies show the potential of NbS to reduce flood hazard and risk at the local scale, there is still limited evidence for the effects of NbS at a catchment scale (Ruangpan et al., 2020). Particularly challenging is the validation of modeled NbS benefits, which is important to emphasize the robustness of risk reduction by NbS. Empirical evidence of the hydrological and hydrodynamic effects of NbS is limited, particularly concerning catchment-level applications of NbS (Ferreira et al., 2020; Lalonde et al., 2024),. A reason for this lack of empirical evidence is that catchment-wide NbS-projects are rare (Kumar et al., 2021). Moreover, it takes time for many NbS to become effective, especially concerning NbS that involve the planting of trees and other vegetation (Kumar et al., 2021), which means that the effectiveness of recently constructed NbS-projects cannot be assessed yet.

Furthermore, only a few studies (e.g., Lallement et al., 2021; Pudar et al., 2020; Ruangpan et al., 2024) have monetized the flood risk reduction effect of NbS . For example, Lallement et al. (2021) showed that reforestation can reduce flood risk by $1 million/year by 2040 for a catchment in Myanmar. Pudar et al. (2020) calculated that detention ponds can reduce flood risk by €3.45 million/year in Serbia. Ruangpan et al. (2024) investigated the effects of several NbS for a catchment in Serbia. They find a flood risk reduction of €0.488 million/year for reforestation, €1.394 million/year for retention ponds and €0.0097 million/year for floodplain restoration.

These previously mentioned studies on the performance of NbS for reducing flood risk seem promising. Yet in practice, the uptake of NbS is still limited because knowledge is missing at a catchment level where other measures could be considered as well (Opperman & Galloway, 2022). The majority of NbS-studies focuses on modelling the effect of only one local NbS measure (e.g. Lallement et al, 2021; Pudar et al.; 2020). In reality, several of these measures can be implemented simultaneously in a river catchment. As NbS have complex hydrological and hydrodynamic effects, it is possible that the implementation of certain NbSs positively or negatively impact the performance of other Nb or of other flood risk reduction measures (Lalonde et al., 2024; Vigerstol et al., 2023). Flood hazard assessment tools need to integrate more complex dynamic relationships between measures in order to support the planning of NbS-strategies that maximize risk-reduction or that are most cost-effective (Vigerstol et al., 2023).

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Furthermore, to make informed decisions, there is a need to compare the effectiveness of NbS to other measures, such as technical or building-level adaptation measures. However, in the current literature, NbS are only compared to large-scale flood protection measures such as dikes (e.g., Pudar et al., 2020; Vojinovic et al., 2021; Turkelboom, 2021). A model framework that allows a robust and relatively low-effort comparison of different flood risk-reduction measures, including multiple NbS, as well as dikes, increases the ability of flood risk managers to select optimal (most beneficial, most cost-effective, etc.) flood risk adaptation measures.

3.2 Exposure modelling

So far, using flood hazard modeling, we are able to assess with certain probabilities where land will be inundated by floodwater, and how deep this floodwater will be. The next step that is needed to estimate a monetary figure of flood risk, is to determine how much economic value is located within the inundated land. Flood exposure comprises the economic value of assets located on land that is expected to be inundated by floodwater with a certain probability. A robust analysis of flood exposure is important to estimate the economic value of NbS and other flood adaptation scenarios, and it is also essential for insurers to accurately determine premiums charged for covered risk.

There are essentially two analyses to perform when assessing flood exposure. Firstly, an account of what is located on inundated land needs to be established. Secondly, an economic value needs to be assigned to the exposed assets.

An assessment of flood exposure requires a spatial overlay of the expected flood extent with a map that includes information on land-use. Decisions need to be made concerning the level of detail of asset-classes that are included in the exposure analysis. Large-scale flood risk analyses may choose to generalize exposure into a single category that represents all built-up space in a flooded pixel. For example, the global flood risk model GLOFRIS (Ward et al., 2017; Winsemius et al., 2016) estimates exposure as the percentage of a spatial cell that is built-up, which is estimated using satellite imagery. An assumption is made where fixed shares of the built-up environment per cell are used for residential, commercial, and industrial purposes. A more refined, but more data intensive approach is to identify exposure using different land-use classes. The CORINE land cover map is an often-used database for flood exposure assessments, as it has global coverage, on a quite detailed (100 meter) resolution. This land cover map identifies 44 different land-use classes, including agriculture, residential, and infrastructure.

Although the methods for estimating flood exposure described above are useful for large-scale assessments, they may lack the level of detail required for insurers to set risk-based premiums. Moreover, certain NbS and other flood risk adaptation measures are beneficial by reducing flood exposure, which can be assessed more precisely using an object-based approach. Recently, there has been increasing interest in developing and using object-based datasets instead of the established aggregated methods of projecting flood exposure (Sieg et al., 2023). Object-based datasets are particularly valuable because of their high spatial accuracy (Sieg et al., 2023), and their ability to connect specific characteristics to mapped objects (e.g., Englhardt et al., 2019). For example, object-based datasets may include information on the elevation of buildings, the number of floors, and the type of structure (e.g., wooden bungalow, mobile home, stone or concrete structure, etc.). Object-based datasets have, thus far, been used for mapping buildings (Englhardt

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et al., 2019; Sieg & Thieken, 2022), infrastructure (Van Ginkel et al., 2021; Bubeck et al., 2019; Kellerman et al., 2016) and cultural heritage (Figueiredo et al., 2020).

An often-used resource for object-based exposure assessments is OpenStreetMap (OSM) (Sieg et al., 2023). Several studies have assessed the accuracy and completeness of OSM data. Chehreghan and Abbaspour (2018) demonstrated that roads extracted from OSM have a spatial accuracy of 92% compared to a reference dataset, while globally the completeness of the roads is around 83%, with over 40% of all countries having a complete dataset (Barrington-Leigh & Millard-Ball, 2017). Regarding buildings, the completeness of OSM data is documented to exceed 80%, with the regions of Europe, Central Asia, and North America demonstrating the highest level of completeness (Herfort et al., 2023). The completeness of OSM data has rapidly been improving in the last few years (Sieg et al., 2023). Several studies have successfully used OSM data in their flood risk analyses (Sieg & Thieken, 2022; Sieg et al., 2019; Figueiredo et al., 2020; Bubeck et al., 2019; Koks et al., 2019).

After establishing the structures and assets that are located in a floodplain, the next step in estimating flood risk is to determine the economic value of these exposed assets. This is a complex task that often in flood risk modeling requires simplifying assumptions. Large-scale catastrophe models often relate the monetary value of exposed assets to regional or national GDP. One way this may be applied is by approximating the exposed population and multiplying this with per capita GDP and an additional factor that represents the accumulation of capital by individuals (see Jongman et al., 2012 for a demonstration of this approach). This method is useful for large-scale flood risk assessments that lack information on exposed buildings. Although the method connects exposed economic value to GDP, it does not account for different types of land-use. For example, exposed economic value may be much higher in industrial areas than in residential areas, which cannot be captured using the exposed population method. A more robust approach is to connect exposed economic value to the type of land-use (Jongman et al., 2012). An economic value can be assigned to each identified land-use exposed to flooding. This approach to assessing flood exposure is able to differentiate exposed economic value between, for example, mainly residential areas and areas where capital intensive industries are located. For large-scale assessments, the economic value of each land-use class may still be connected to regional/national GDP per capita to capture spatial differences in asset values. Asset values are mostly used to capture maximum damage, which occurs with a certain flood water depth. A lower water depth is usually associated with damage below this asset value. This process is described in more detail in Section 3.3.

3.2.1 Limitations in current exposure modeling

Flood risk assessments that distinguish land-use classes and differentiate asset values accordingly are able to capture important spatial information that may drive flood risk. Such information may be important when making decisions about adaptation, such as prioritizing investment in flood protection infrastructure. However, the state-of-the-art in flood exposure assessments is considered too coarse to capture important information that drives flood risk (Englhardt et al., 2019). Object-based flood risk assessments may benefit from more detailed information regarding asset characteristics and values. There are small-scale flood risk assessments that include more detailed spatially explicit information on structures, including building materials, ground floor elevation, and number of floors (Godfrey et al., 2015), or on asset values, such as property prices

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(Röthlisberger et al., 2018). A driving factor concerning the level of spatial detail in flood exposure modeling is data availability. Detailed small-scale assessments may be feasible with the availability of local datasets, for example facilitated by local governments or insurers, or by on-the-ground data collection by researchers. For large-scale assessments this becomes much more difficult, as the required data for many regions may not exist or is unavailable due to data privacy policies.

3.3 Vulnerability modelling

The remaining component of flood risk modeling in this review, flood vulnerability, captures the relationship between flood inundation and physical damage to exposed economic assets. Also concerning modeling flood vulnerability, there are different approaches available, and the choice of method to apply in a flood risk assessment is largely dependent on available data, as well as on how flood hazard and exposure are simulated. An often-applied method for simulating flood vulnerability in flood catastrophe models is a stage-damage curve, also known as flood depth-damage curve. As the name indicates, these models capture the relationship between inundation depth and the damage it causes to a certain land-use type, making such curves suitable to be applied in flood risk models that estimate flood inundation depth (see Section 3.1). Stage-damage curves are available for different building types and land-use classes on a global scale (Huizinga et al., 2017). The often-applied stage-damage curves by Huizinga et al. (2017) are developed for each continent separately, which are rescaled to country-level by adjusting the maximum damages in these curves based on country-level construction sector costs.

Stage-damage curves can be developed to capture more specific local vulnerability to flood inundation. Continent-level depth-damage relationships fail to consider differences in, for example, local building practices and materials. The estimation of a location-specific depth-damage relationship will capture physical vulnerability as a result of local exposure or hazard characteristics, such as building standards and flood water velocity (Endendijk et al., 2023). Such bivariate analyses (flood damage as a result of flood depth) are, however, inherently representative of flood vulnerability for the geography captured by the underlying flood inundation and damage data. Therefore, the applicability of these curves to other regions may be limited. To improve the applicability of flood vulnerability assessments, multivariate models are developed to consider a range of variables that affect flood impacts on exposed people and property (Endendijk et al., 2023; Malgwi et al., 2020). Multivariate flood vulnerability models statistically assess the influence of a range of variables on flood impacts, potentially including building and population characteristics, but also flood hazard conditions. Multivariate models may, therefore, statistically control for location-specific information that may impact the depth-damage relationship. As a result, a tailored depth-damage curve may be applied for specific regions in a flood risk simulation based on relevant regional characteristics. Applications of a multivariate approach to flood vulnerability modeling are increasingly popular (Kreibich et al., 2016; Wagenaar et al., 2017; Endendijk et al., 2023).

What makes multivariate flood vulnerability models particularly attractive is their ability to consider both physical and social aspects that influence flood damage. These models usually aim to capture the relationship between different social and environmental characteristics, and physical flood damage. Examples of social factors influencing flood damage are gender, education level, age or employment (see Fernandez et al., 2016). Importantly, these analyses do not capture the impact of flood extent on social outcomes, such as (mental) health, income, and well-being. A vulnerability

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index method may be applied to capture this broader social vulnerability to floods (e.g. Fernandez et al., Cutter et al. (2003). This may be done by assessing, empirically or qualitatively, characteristics that affect social impacts of floods and then, spatially quantifying flood vulnerability based on socio-economic exposure data. The resulting flood vulnerability index may be combined with flood hazard data to obtain a figure capturing the social dimension of flood risk. Several studies apply a flood vulnerability index approach to assessing flood risk (Koks et al., 2015; Forrest et al., 2020). Importantly, using a flood vulnerability index approach does not produce a numerical estimate of flood risk, which makes it less attractive for applications in cost-benefit analyses to inform decision-making on flood mitigation and adaptation (Kind et al., 2019). However, since the social dimensions of flood impacts are no less important than the physical impacts, it is recommended that policymakers apply a combination of flood vulnerability measures (Papathoma-Köhle et al., 2019).

3.3.1 Limitations in current vulnerability modeling

A major limitation concerning the robustness of applied flood vulnerability models is data availability (Englhardt et al., 2019; Endendijk et al., 2023; Wagenaar et al., 2018). The application of stage-damage curves requires robust training data that captures the relationship between different flood depths and the resulting damages. The estimation of this relationship in a particular region may, therefore, require the collection of closely monitored data on the flood event and resulting damages. As floods are mostly rare events, collecting sufficient data for an analysis of a specific region may be challenging. Insurance companies covering flood risk are often particularly well-placed to collect and analyze data on the impacts of a flood event. Often, however, insurers are reluctant to share data and insights into their risk portfolio for reasons of data privacy and/or business competition. Exceptions are presented in Wing et al. (2020) and Wang and Sebastian (2021), who construct flood depth-damage curves for several areas in the US by using big data obtained from the National Flood Insurance Program (NFIP), a public insurance provider in the US. Alternatively, when empirical flood damage data is unavailable, such data may be collected using a survey method, as done by Thieken et al. (2005) to study flood impacts of the 2002 floods in Germany, and Endendijk et al. (2023) to gather flood impact data after the 2021 floods in the Netherlands. Moreover, there is also limited detailed local data available on social vulnerability at a global scale (Fox et al., 2024), which limits the usefulness of a social vulnerability index.

Relating damages to flood depth also requires accurate insights into the water depth that causes a specific level of damage for a particular property. The NFIP database used by Wing et al. (2020) contains information on inundation depth for individual properties, as estimated by loss-adjusters evaluating damaged properties. As such measurements of flood depth are mostly unavailable for specific flood events, relevant insights are often gathered based on subjective perceptions of affected households, as done in the surveys by Thieken et al. (2005) and Endendijk et al. (2023). A downside of this approach is that it is prone to bias caused by the under- or over-estimation of inundation depth by respondents (Thieken et al., 2005). Another approach to estimate the flood inundation depth is to simulate the specific event in a hydrologic-hydrodynamic model, using input parameters (e.g., meteorological conditions) that are similar to those that caused the flood to occur. Although this approach may increase the potential modeling bias (as the hydrologic-hydrodynamic model is used to estimate both hazard and vulnerability in the flood risk assessment), this may be reduced by thorough calibration and validation of the flood hazard model. Such an approach to estimating flood inundation is applied by, for example, Wang and Sebastian (2021).

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The challenges posed by data scarcity are even more severe for multivariate flood vulnerability models. This is because such models may require measurements of a range of additional variables that can be causally associated with flood damage. Besides data on flood depth, such models may also require information on flow velocity and flood duration (Thieken et al., 2005), but also characteristics of buildings (Wagenaar et al., 2017) and populations affected by the flood, depending on the scope of the model. Again, many of these variables may be available to insurers covering flood risk. In some regions, accurate spatially explicit datasets on building characteristics exist, such as the Dutch BAG database, which describes building size, function, and approximated value. Alternatively, object-based datasets such as OpenStreetMap (OSM) may provide valuable information on the purpose of individual structures (e.g., residential, commercial, industrial, etc.). Data describing population characteristics on property-level exists in many regions but is mostly difficult to access due to privacy concerns.

Although some building and population characteristics may be gathered relatively easily, data on flood characteristics may be more difficult to obtain. Flow velocity is virtually impossible to measure after the flood has taken place. Some hydrodynamic models do capture flow velocity (Kreibich et al., 2009), which could be an interesting source for this information. Flood duration may also be assessed using hydrodynamic models, but can also be observed through satellite imagery, as provided by NASA and ESA. A holistic method for obtaining the data needed for a multivariate flood vulnerability model is a survey approach, as applied by Thieken et al. (2005), Endendijk et al. (2023), and Wagenaar et al. (2018). Since households impacted by a flood are the subject of a multivariate flood vulnerability assessment, many variables of interest may be most efficiently and effectively collected through a household-survey.

3.4 Illustration of improved risk-reduction metrics

The highlighted limitations concerning existing methods of modeling NbS benefits are addressed in a study that aims to assess the flood risk reduction capacity of various NbS in an area of the Netherlands that was flooded in July 2021. This study assesses several NbS, that were co-designed with relevant stakeholders throughout one of NATURANCE's innovation labs. The main aim of the study is to compare the risk reduction of two NbS: reforestation and retention ponds. Besides focusing on these NbS, model improvements aim to allow for an object-level assessment of flood risk, which is a valuable innovation for insurance applications, as discussed in the introduction of Section 3 of this report.

The innovations include the coupling of a hydrological and hydrodynamic model to an object-based flood risk model, using building-level exposure and vulnerability data. This coupled model allows for a detailed object-based scale assessment of flood risk impacts. The model is applied to the Geul river in the South of the Netherlands. The Waterboard in this region (a governmental organization responsible for water management) is currently developing NbS such as retention ponds. This study provides additional information on the effectiveness of such measures.

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3.4.1 Case study description

The Geul is a tributary of the Meuse and its catchment is located in the Netherlands, Germany and Belgium (see Figure 3.1). The catchment of the Geul is characterized as hilly, with elevation differences between 50 and 340 meters over a 58 km distance. The catchment lies in a temperate zone, with yearly average precipitation of approximately 870 mm/yr. Within the catchment, land-use is predominantly made up of agriculture on plateaus, forests on steeper hills and grassland within river valleys. Due to the hilly terrain, the Geul and its tributaries respond fast to rainfall events, making flash floods during heavy rainfall events a substantial hazard. For the Dutch part of the Geul, protection standards are designed to withstand a 1 in 25-year flood (ENW, 2021), which is maintained by the local water authority (water board Limburg).

As a result of intense and persistent rainfall within the Geul catchment in July 2021, the river's estimated peak discharge of 100 m^3/s (ENW, 2021) caused flooding at several locations in Germany, Belgium and the Netherlands. Within the Dutch part of the catchment, the flood was particularly destructive, with flood damages estimated at €250 million (ENW, 2021).. The flood of 2021 triggered an ongoing discussion concerning flood risk management in the catchment, including the development of new flood risk adaptation measures (Jonkman et al., 2023).

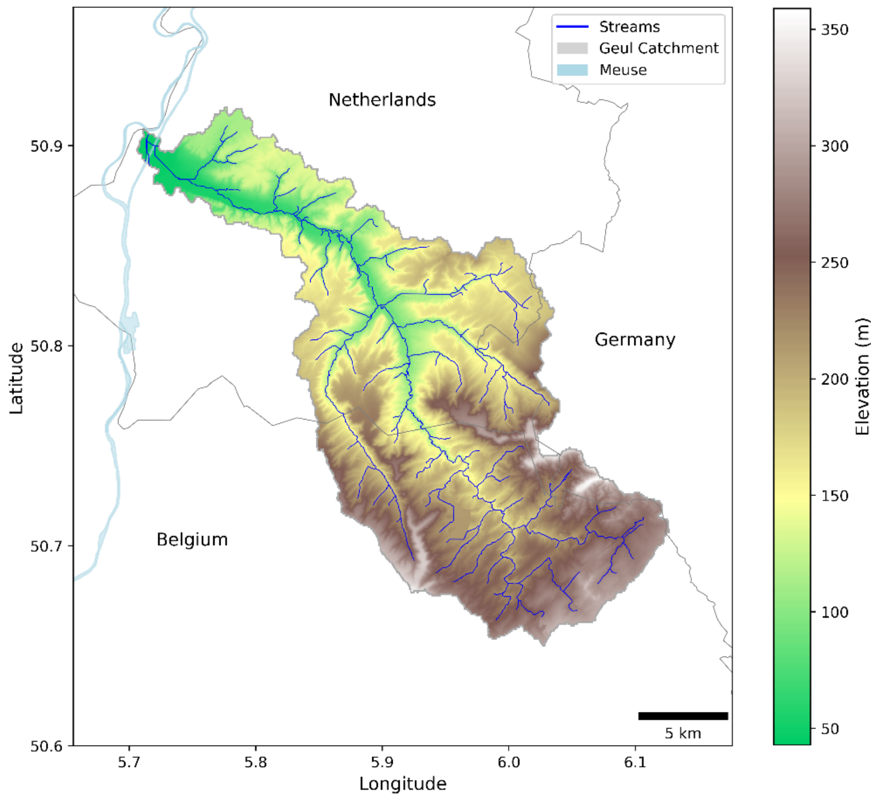

Figure 3.1 Location of the Geul River catchment showing elevation differences

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3.4.2 Methodology

Our efforts to improve metrics for assessing flood risk reduction resulting from NbS-measures involve the three main elements generally applied in flood catastrophe models, which are hazard, exposure, and vulnerability. Figure 3.2 presents an overview of the modeling setup applied for this research.

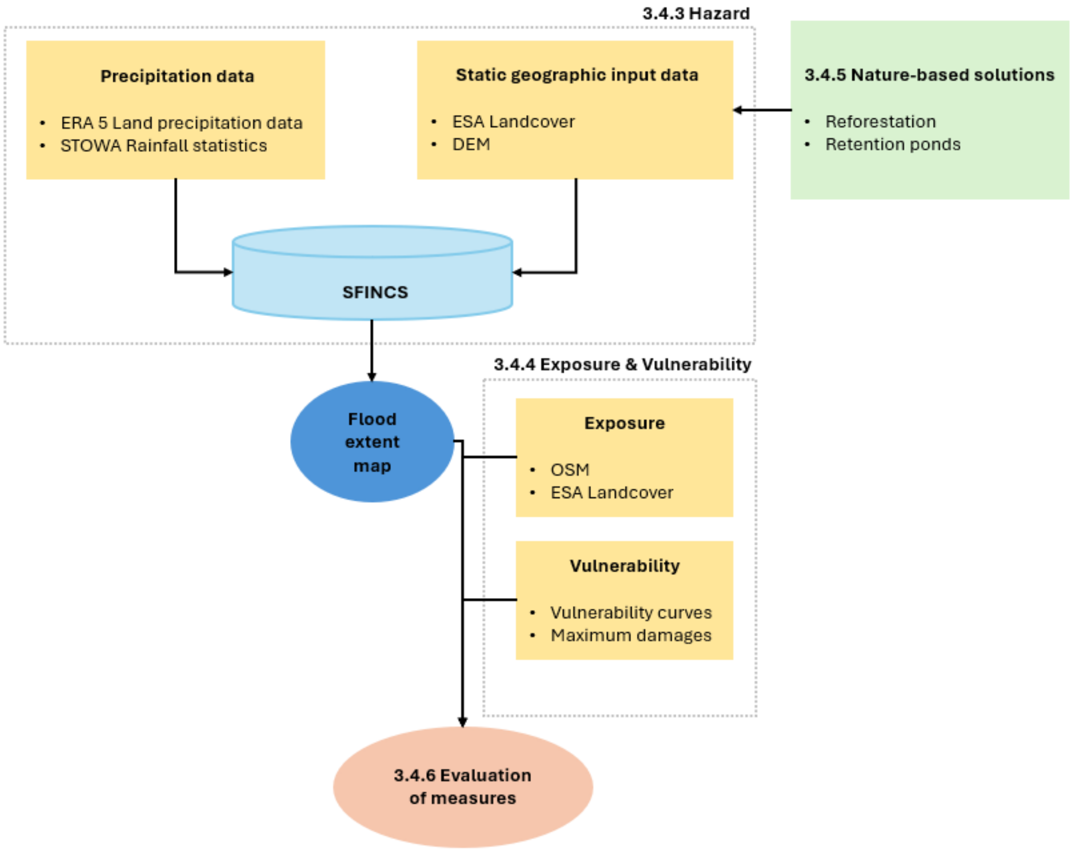

Figure 3.2 Framework depicting the modelling steps taken in the analysis

In Figure 3.2 we can see that a flood hazard module (3.4.3) applies a single model (SFINCS) to simulate flood inundation, which applies probabilistic meteorological data, as well as static geographic data. SFINCS is an established flood hazard model. Assessed NbS-measures are presented in 3.4.5, which affect the static geographic input data applied in the coupled hydrologic-hydrodynamic simulation. The output of the flood hazard module are maps of flood extents and corresponding depths associated with different probabilistic events. These flood maps are applied in an exposure and vulnerability module (3.4.4) to estimate flood risk. The flood exposure data is represented at an object-based level using OpenStreetMap (OSM). Additionally, the ESA landcover map is used to represent exposure of land-use classifications not used in OSM. The flood vulnerability of exposed assets is represented by stage-damage curves designed based on a dedicated survey in the case study area. Model output (3.4.6) includes the monetary value of flood risk reduction resulting from the assessed NbS-scenarios. Each of the model components developed for this research is described in more detail below.

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3.4.3 Flood hazard

SFINCS model

SFINCS is a 2D-hydrodynamic model with reduced complexity, allowing rapid simulations (Leijnse et al., 2021). The model applies simplified Saint-Venant equations to represent the mass and momentum of overland flow and river discharge. SFINCS has been elaborately applied and tested to simulate various types of flooding, including coastal, compound and riverine flooding (Leijnse et al., 2021; Parodi et al., 2020; Röbke et al., 2021). Although SFINCS can be flexibly applied using various types of forcing data, for this research solely precipitation data is used to force the simulation, as the Geul does not receive inflow from other river systems.

Precipitation data

Our starting point for the precipitation data is the event that happened during July 2021. We use the ERA5-Land dataset for the time period 02-07-2021 to 16-07-2021 (Muñoz Sabater, 2019). During the peak of the event, the accumulated rainfall amounted to 96 mm over 48 hours. This corresponds to an event that is expected to occur once every 50 years in this region. To be able assess flood risk we need precipitation data associated with a range of probabilistic events, which is estimated by scaling the 1–in-50-year rainfall data observed for this flood event to Dutch national extreme value rainfall statistics from STOWA (Nicolai et al., 2024).

Land use data

The land-use data that we apply to simulate hydrologic and hydrodynamic processes in SFINCS is derived from the ESA Worldcover 2021 map (Zanaga et al., 2022), which presents a wide range of land cover at 10m spatial resolution. The effect of different types of land-coverage on the speed of waterflow and accumulation of river discharge is assessed by differentiating the Manning's roughness indicator for these various types of land cover. Table 3.1 presents these specific Manning's roughness coefficients, which are adapted from Deltares (2024)

Table 3.1 Manning's roughness coefficient per land use category (adapted from Deltares, 2024)

Land use	**Manning's n**
Tree cover	0.12
Shrubland	0.05
Grassland	0.034
Cropland	0.037
Built-up	0.1
Bare / sparse vegetation	0.023
Snow and ice	0.01
Permanent water bodies	0.02
Herbaceous wetland	0.035
Mangroves	0.07
Moss and lichen	0.025

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3.4.4 Exposure and vulnerability

Exposure

Flood exposure is assessed using an object-based approach by combining spatial data from OpenStreetMap (OSM) and the ESA WorldCover database. OSM is used to assess the extent to which individual buildings, roads, and railways are located in zones expected to be inundated with a certain probability. OSM data is reported to present more than 80% of the built-environment and include information on the function of the building (e.g., whether a residential or commercial building) for most parts of the world (Herfort et. al., 2023). OSM has recently become a widely used and well-established method for representing exposure (Koks et al., 2019; Bubeck et al., 2019; Sieg & Thieken, 2022). The ESA WorldCover database is used for the assessment of exposed agricultural and natural land.

Vulnerability

We apply stage-damage curves to assess flood damage caused by inundation of exposed objects and land. Figure 3.3 presents the stage-damage curves applied in this research, which show the share of a structure's value that is damaged as a result of flood inundation in meters. The stage-damage curves are separated for various structure and land-use classifications. For the structure and content of buildings, our stage-damage curves are derived from empirical data that was collected after the 2021 flood in the case-study area by Endendijk et al. (2023). The vulnerability of roads is taken from van Ginkel et al. (2021), and for railways from Kellerman et al. (2016).

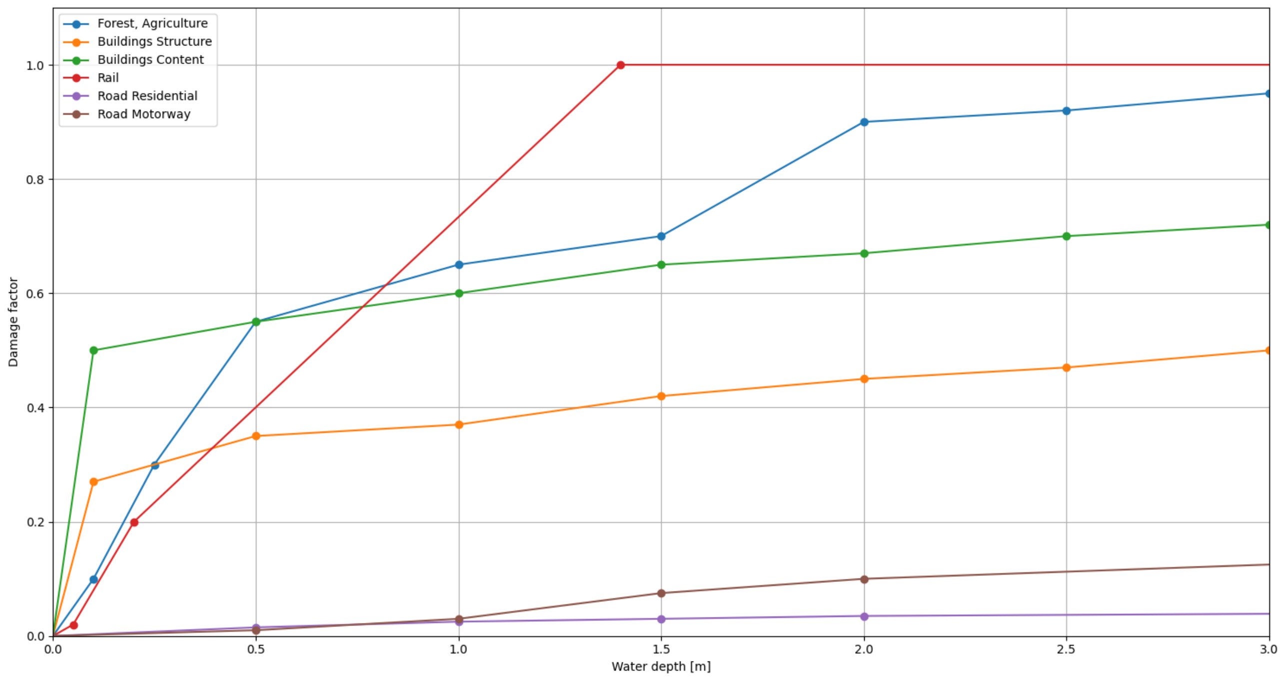

Figure 3.3 Summary of the vulnerability curves used in this study

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3.4.5 Nature-based solutions

We apply two types of NbS and compare the monetary figure of flood risk to a baseline, which is the current state of flood risk in the Geul catchment.

2. Reforestation: In section 3.1 it was explained how vegetation of slopes increases infiltration and reduces the speed of overland flow of rainwater. Increasing vegetation in the Geul catchment may therefore reduce flood risk. Figure 3.4 presents a map showing the areas where reforestation is projected under this NbS-scenario (these are areas currently used by agriculture). We simulate the effectiveness of reforestation on reduced flood risk by changing Manning's roughness coefficient from the value associated with current land-cover (e.g., cropland = 0.037) to the value associated with tree cover (0.12) (see table 3.1). Moreover, we change our input maps showing infiltration properties, such as hydraulic conductivity, effective storage and maximum storage.

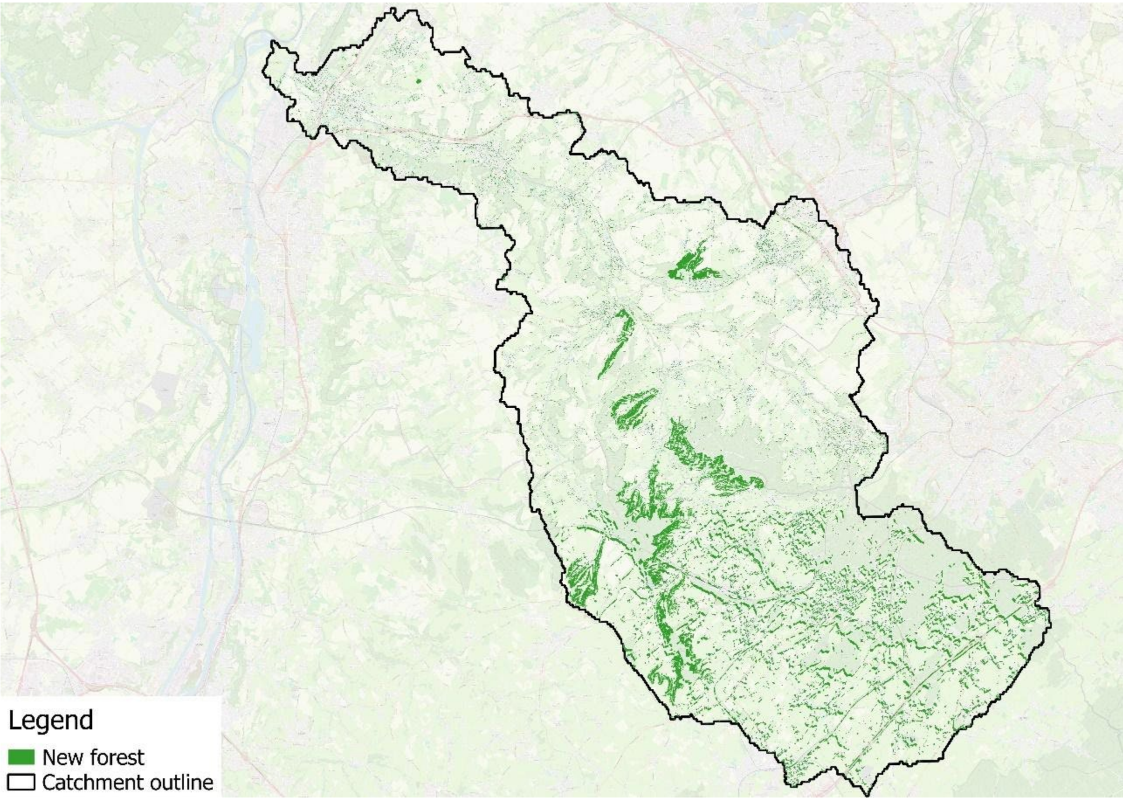

Figure 3.4: Areas where reforestation is projected under this NbS-scenario

2. Retention ponds: Flood retention ponds are used to temporarily store water in the case of peak river discharge, reducing the accumulation of discharge downstream. Retention ponds are already applied in the case study area, but we developed and applied an NbS-scenario where the number and size of such ponds are increased throughout the catchment (see Figure 3.5 for the exact location of these new storage ponds). In the flood hazard module, we assign a flood storage volume for each spatial

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cell, based on the availability of floodwater storage in the cell. Only once the storage capacity has been exceeded, can floodwater exceed embankments and cause a flood.

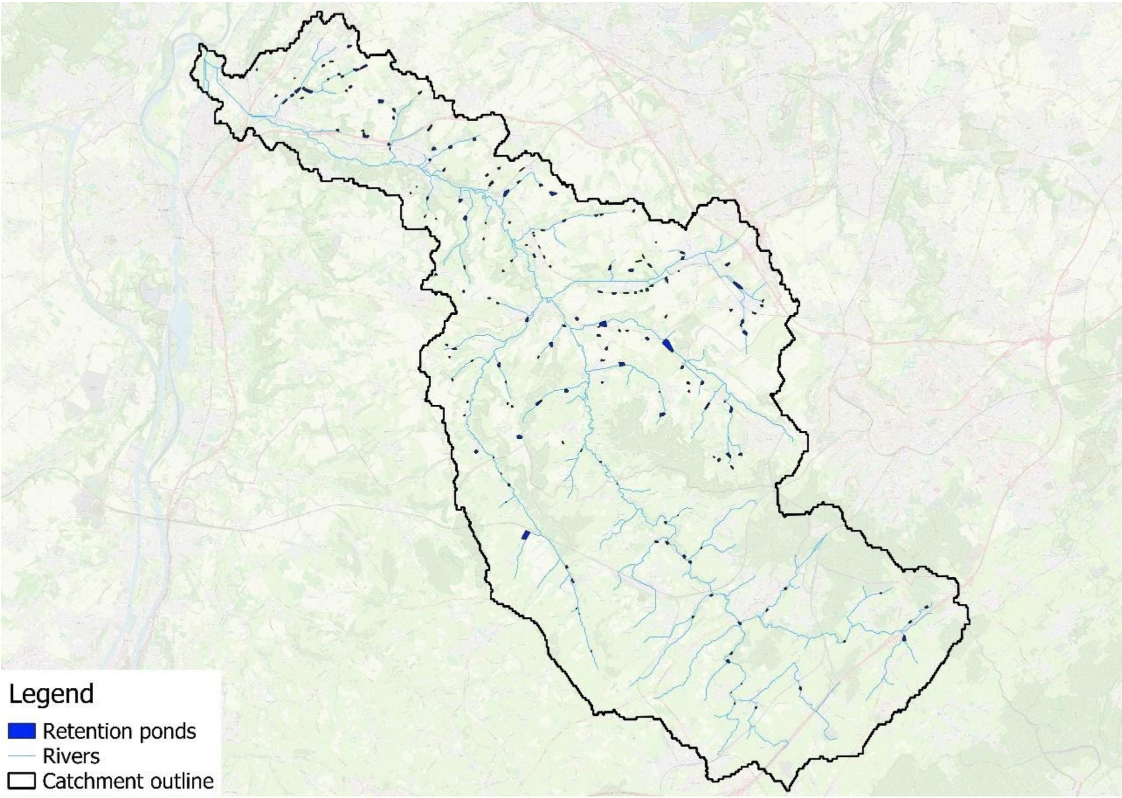

Figure 3.5: The location of new flood storage ponds under this NbS-scenario.

3.4.6 Results

The results of our object-based flood risk assessment for the Geul catchment are presented in Table 3.2 for the baseline scenario (which resembles the current situation in the catchment), as well as for the two NbS-scenarios. We can see that Annual Expected flood Damage (EAD) declines by €0.8 mln/yr under the reforestation scenario and by €0.1 mln/yr under the scenario with increased storage ponds. Besides EAD, we can see the amount of damage associated with specific probabilistic rainfall events (return periods). We can see that the reforestation scenario is more effective at reducing flood extent, average water depth, and monetary damages compared to the storage ponds. The effectiveness of both NbS-measures at reducing flood risk is higher for the more frequent events (25 and 100-year events). Under the most extreme event (1000-year flood), reforestation is still effective at reducing flood risk, but less so compared to the 25- and 100-year floods. However, storage ponds are no longer effective at reducing flood risk during a 1000-year event.

At the bottom of Table 3.2 we can see the costs associated with each NbS-scenario, as well as the benefit-cost ratio (BCR). Storage ponds are cheaper to implement than reforestation, but are less effective at reducing flood risk, causing the BCR to be lower than for the reforestation scenario. As the BCR for the storage ponds scenario is smaller than one, the reduced flood risk is insufficient to make this an attractive investment. However, when co-benefits of storage ponds are assessed (e.g., increased biodiversity), perhaps this measure can become cost-effective. Since the BCR for reforestation is more than 1, this NbS-scenario is an attractive investment to reduce flood risk.

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Considering co-benefits, the BCR will likely be even higher. However, it must be noted that within the cost estimate of reforestation, we do not consider the purchasing price of land from farmers, nor the opportunity costs of the land that will be used for reforestation. Including these potential costs causes the BCR to drop to 0.17.

Table 3.2: Overview of flood risk under the baseline and two NbS-scenarios

	Return period	Baseline	Reforestation	Storage ponds
EAD		11.3 €mln/yr	10.5 €mln/yr	11.2 €mln/yr
Damage	25	241 €mln	226 €mln	238 €mln
	100	312 €mln	287 €mln	310 €mln
	1000	439 €mln	415 €mln	439 €mln
Flood extent	25	11.84 km2	11.82 km2	11.75 km2
	100	13.69 km2	13.14 km2	13.65 km2
	1000	16.57 km2	15.99 km2	16.55 km2
Average water depth	25	0.60 m	0.56 m	0.59 m
	100	0.67 m	0.60 m	0.66 m
	1000	0.84 m	0.76 m	0.84 m
Costs		-	14 €mln	8.2 €mln
BCR		-	1.06	0.24

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4 Physical modelling of ecosystem services of NBS

In this section, we aim to discuss models and methods for assessing the non-monetary co-benefits of NBS, with a particular focus on their application in the context of climate change.

The stock-taking conducted in D4.1 identified a variety of economic and non-economic methods for the (semi-)quantitative assessment of NBS co-benefits. These methods, which can address multiple co-benefits and also disservices, are context-specific but can be replicated and scaled. Key challenges include the lack of standardized methodologies and indicators, data availability, and the limited consideration of future climate change impacts on NBS efficiency. Despite these limitations, combining field samplings, literature reviews, and stakeholder knowledge could improve data availability and help reveal the positive and negative effects of NBS across locations. Integrating models, statistical analyses, and stakeholder engagement could enhance assessments and comparability, supporting the broader adoption of NBS.

4.1 How to assess the long-term effectiveness of NBS in coping with climate and environmental challenges?

In the context of climate change, it is crucial that NBS and ecosystems are resilient enough to survive and continue providing vital services under future climatic conditions (Calliari et al., 2019; EEA, 2021). This resilience must also account for changes in future land use patterns and socio-economic systems. To comprehensively assess NBS, a variety of interconnected elements need to be considered, including vegetation, soil and water, biodiversity, and the dynamic interactions between these components. These factors are strongly influenced by climate, land use changes, socio-economic development, and ecological conditions, all of which play critical roles in shaping the ability of ecosystems to adapt and maintain their functions over time (Veerkamp et al., 2021).
To effectively respond to these challenges, advanced methods such as ecosystem models and impact- and process-based models can play a pivotal role. Ecosystem models enable the simulation of complex ecological interactions and their responses to changing climatic and environmental conditions, helping to predict potential shifts in ecosystem structure and function (Geary et al., 2020). Impact and process-based models provide detailed insights into specific processes, such as water flow, nutrient cycling, and carbon sequestration, allowing for a more precise evaluation of how NBS can mitigate climate impacts (Cuddington et al., 2013; Lazarova, 2017). Together, these tools offer a robust framework for designing, monitoring, and optimizing NBS to ensure their effectiveness in addressing both current and future challenges.

Ecosystem models and impact- and process- based models are widely used in academia but often face challenges in an operational context. This is primarily due to their high computational demands and the difficulty of obtaining the necessary input data at the high spatial resolution required for site-specific or small regional scale applications. Despite these limitations, their added value lies in their ability to simulate future scenarios and provide critical background information. This forward-looking capability complements more 'conventional' risk-assessment models by offering insights into how NBS implemented today might perform under future climatic, ecological, and socio-economic conditions. By integrating these models into decision-making processes, it becomes possible to better understand the long-term effectiveness of NBS, allowing for more informed planning and adaptation strategies. Software and tools, such as InVEST, i-Tree eco, TESSA and

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others, can support and simplify integrated spatial assessment of ecosystem services and processes by providing by user-friendly interfaces and guidelines, or ready-to-use codes (Tardieu, 2017; D4.1). However, some limitations remain, particularly in terms of data needs and future climate change analysis (see D4.1 for further details).

In this perspective, enhanced collaboration between scientists, investors, insurers, and decision-makers is crucial to address knowledge gaps, link research with insurance models, and foster robust evidence on NBS performance under climate change. Bringing together diverse scientific communities working on various aspects of the same topic can create synergies that drive innovative, holistic approaches. Such partnerships could promote tailored, transformative decision-making that values NBS benefits in terms of welfare, well-being, and long-term sustainability. Hence, stakeholder engagement techniques can support the definition of NBS, future scenarios, and strategies to maximize the benefits of NBS for society and the environment (EEA, 2021).

4.1.1 Projections of future land use change under different socio-economic and climate changes

Land use often competes across various sectors, and the implementation of NBS, as well as efforts in nature protection and restoration, can exacerbate this competition for space. This can result in trade-offs, such as a decline in the production of services like food, fodder, and timber, potentially leading to intensified production on remaining designated lands or displacement of production to other areas. While these changes can be framed as long-term designations, their effects may vary over time, especially under the influence of global change.

To address these complexities, it is essential to analyze NBS and land use changes as part of the broader land system. This approach ensures that ecosystem services are not unnecessarily compromised, either directly or indirectly, while also considering the uncertainties posed by future climatic and socio-economic conditions. Tackling this challenge requires comprehensive cross-sectoral analyses that integrate both biophysical and socio-economic factors across a range of possible future scenarios (Chatzimentor et al., 2020). Land use change model, such as CRAFTY, can support this type of analysis and considerations. CRAFTY is an agent-based model, fully open-source, designed to simulate land use changes over time, considering climate change and socio-economic scenarios while assessing ecosystem services (Murray-Rust et al., 2014). It provides an efficient framework for modeling land use across large geographic areas, driven by the decision-making of simulated land managers. These agents manage various land uses, producing ecosystem services such as provisioning, regulating, cultural, and supporting services. CRAFTY is available both at European and at national level for some countries (e.g. Brazil, Scotland, Great Britain, Germany). Further details are provided in Brown et al. (2019) and Brown et al. (2021).

At the European level, CRAFTY has been used to assess the impact of expanding EU protected areas to meet the 2030 Biodiversity Strategy, aiming to protect 30% of land, with 10% under strict protection (Staccione et al., 2023). The study found that prioritizing connectivity in new protected areas could meet the strategy's targets without compromising ecosystem services, including food production. However, the influence of the protected area network on land use and ecosystem services varies across different climatic and socio-economic scenarios. The strength of protection had limited effects, with extractive services (food, fodder and timber production) decreasing in protected areas but non-extractive services (carbon sequestration, recreation and landscape diversity) increasing, and compensatory changes occurring outside the network. Changes were small

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where competition for land was low and scenario conditions were benign but became far larger and more extensive where competition was high, and scenario conditions were challenging. The findings suggest the EU's targets are achievable but highlight the need for adaptation in the wider land system to manage spatial and temporal patterns of ecosystem services.

In Sweden, CRAFTY explored how different forest management approaches, climate change, and societal demands impact land use and ecosystem services (Blanco et al., 2017). Forest management approaches vary from the prioritization of timber production to conservation, from the maintenance of recreational and aesthetic value to the maximization of economic returns to enhancing climate change adaptation potential of the forest. These behaviors are modeled to understand how different decision-making processes influence land-use changes and the provision of ecosystem services under various socio-economic and climatic scenarios. The study simulates future changes under various socio-economic and climatic scenarios from 2010 to 2100. The findings suggest that socio-economic changes and behavioral differences among landowners have a more significant impact on land use than climatic changes.

The combination of modelling and stakeholders' engagement can be beneficial for the identification of future scenarios, pairing both climatic and socio-economic conditions. Brown et al. (2022) shows an example of this approach in Great Britain. By integrating stakeholder-elaborated socio-economic (UK Shared Socioeconomic Pathways) and climatic scenarios (Representative Concentration Pathways), the model captures diverse behavioral, social, and societal conditions. The findings reveal that changes in social and human capital—such as social cohesion, equality, health, and education—can have impacts on land system outcomes that are as significant as technological and economic changes, and comparable to those of climate change. Similarly, Burton, (2020) investigates the synergies and trade-offs between ecosystem services resulting from woodland expansion under various stakeholder 'visions'. The research aims to address global challenges such as climate change, biodiversity loss, and deforestation by exploring how different approaches to increasing woodland cover can impact ecosystem services. The study emphasizes the importance of considering diverse perspectives and objectives in land system research to develop effective strategies for sustainable woodland expansion

4.1.2 Projecting future processes in ecosystems, in response to climate change and land-use change

Ecosystem functioning is central to NBS, but climate change and rising CO_2 levels impact vegetation growth, productivity, and carbon storage in complex ways. These changes also affect NBS related to flood regulation, water quality, erosion, and wildfire risk. Future land-use can either support or hinder ecosystem adaptation to climate change, influencing NBS. To better understand and assess these systems, it is necessary to combine data from vegetation, carbon cycle, and hydrological models.

Dynamic global vegetation models (DGVMs) simulate vegetation growth and interactions of plant, soil carbon, water, and nitrogen dynamics in ecosystems (Prentice et al., 2007). LPJ-GUESS, known for its biological realism, represents vegetation through functional types (e.g., ‘boreal shade-tolerant conifer’, ‘autumn-sown C3 cereal’) based on their growth environment and physiology. For Europe, woody plant functional types (PFTs) map to main tree species. The model's foundation includes physiological processes like photosynthesis, evapotranspiration, and respiration. PFTs in a grid cell compete for resources, influenced by disturbances (i.e. wildfire) and age-related mortality

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(Smith et al., 2014). Inputs include climate data and information on land-use change, the latter can be derived e.g. from CRAFTY simulations. LPJ-GUESS can run at 1km resolution for small regions with appropriate input.

LPJ-GUESS is commonly used to assess climate change mitigation potential under various climate and land use scenarios. A recent study found a projected net global gain in carbon storage up to 110 PgC (2056–2060) in response to strictly protecting 30% and 50% of the land, which is equivalent to around 10 years of current global anthropogenic carbon emissions. However, in the protection scenarios, cropland expansion in some regions was accompanied by local carbon losses and an increase of up to 8% in the use of nitrogen fertilizer, with associated risks of pollution and additional N2O emissions (Camargo-Alvarez et al., 2024).

Ma et al. (2022) found that in Eastern Africa, integrated conservation agriculture (no-tillage, residue and manure application, cover crops) increased soil organic carbon and crop yields compared to conventional methods. Nitrogen-fixing cover crops also showed promise for enhancing soil carbon and crop production, though they resulted in nitrogen losses. These impacts were sustained under three future climate pathways.

A study that explored impacts of forest fire management in Mediterranean Europe found that prescribed burning and thinning both reduced fire intensity, which would reduce risks to human health and well-being although prescribed burning may contribute to respiratory problems. Cumulative carbon uptake until the end of the 21st century declined especially under the influence of thinning, which makes the assessment of net climate change effects challenging (Rabin et al., 2022).

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5 Monetization of co-benefits of NBS

In this section we will delve into how we overcome the barriers and challenges in assessing the monetary co-benefits of NBS for climate risk reduction. The section is structured as follows. First, we will explain the rationale for the use of choice experiments for monetization of co-benefits of NBS. Then we describe the design process of our new choice experiment method for this deliverable, including the input of local stakeholders and building upon the meta-analysis conducted for Deliverable 4.1. Lastly, the improved co-benefits assessment will be illustrated by the results of our choice experiment in the region of Limburg.

5.1 Choice Experiments for co-benefit monetization

This section will delve into how we overcome the challenges of monetizing the co-benefits of NBS, which are typically overlooked and uncertain. Partially, this is because it is challenging to put a monetary value on benefits that do not have a market value, such as aesthetic appreciation or recreation. This was identified as one of the main barriers for mainstreaming investment in NBS, as identified in the stock-taking phase. For example, many existing methods for assessing co-benefits do not monetize these benefits, which may hamper sustainable investment strategies. We aim to overcome this barrier by providing monetary estimations for certain benefits of NbS. However, even when monetized, these co-benefits do not directly translate into a higher return on investment for private sector companies.

An additional challenge is the lack of available data about NbS co-benefit, both from a physical and economic perspective. A way of overcoming this is through valuation studies that focus on local citizens' preferences regarding co-benefits, which then allows the estimation of a monetary value as a “willingness-to-pay" estimate. These valuation studies estimate a monthly or yearly price that respondents would be willing to pay for certain environmental benefits. There is a wide array of methods in environmental economics literature that serve this purpose. Stated preference methods (SP) are the most frequently used option when primary data is not available (e.g. assessing the preferences for a NBS that is planned for a region but has not been developed yet). This is not the only application of SP, as they are also commonly used in transport, health studies or marketing. SP methods require conducting primary research through contingent valuation or choice experiment surveys and consist of describing hypothetical decisions given a context in order to estimate the respondent’s change in utility associated with a proposed increase in the quality/quantity of an ecosystem service. Choice experiments (CE) try to overcome some of the challenges that other SP methods, such as contingent valuation studies, or revealed preferences studies have suffered traditionally. SP methods also have their own limitations, including hypothetical bias. This occurs when the respondents are asked to make hypothetical choices in a scenario presented by the researcher, instead of observing real market data, as it is done in revealed preference studies. This bias is a bigger problem in contingent valuation studies, where the WTP is asked directly to the respondent, as CEs create realistic scenarios. Revealed preference studies (e.g. hedonic pricing) provide incomplete values as they are based on market transactions, which ignores an important fraction of the total economic value of NBS that is still not captured by market prices.

In the field of economic valuation, **CEs** present respondents with a series of hypothetical scenarios where the attributes of a “non-market" good or service are varied, and respondents are asked to

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choose their preferred option from a set of alternatives. Each alternative shows different levels for each attribute. In this case, the attributes (or characteristics) are our different co-benefits. The number of levels vary **for each attribute,** and they show how much that environmental good is improving (e.g. from no extra **warning** time to 30 minutes, 1 hour or 1.5 hours). The levels will help us to monetize these attributes. For example, we can estimate how much individuals are willing to pay for an extra half an hour of warning time. Choice experiments have the advantage of using an attribute-stimulus format that provides more information regarding the different levels of attributes and makes the respondent face realistic trade-offs (Morrison and Bennett, 2000). To ensure realistic trade-offs, the survey must be carefully designed, since a dominant alternative or unrealistic attribute values could increase hypothetical bias. In addition, introducing an opt-out option can also help to reduce hypothetical bias by not asking the respondent to choose between two unattractive alternatives. The opt-out alternative, **preserving** with agricultural land instead of developing NbS, has all levels set to zero and does not represent an increase in cost. The scenario-based approach allows overcoming part of the hypothetical bias present in contingent valuation studies, which traditionally asks directly for the willingness-to-pay for an environmental good or service. Compared to hedonic pricing, using CE for environmental valuation, allows to estimate several simultaneous co-benefits and to disentangle the willingness-to-pay the respondents have for each specific co-benefit.

Our modelling approach follows the Random Utility Theory (McFadden, 1977), which assumes that individuals select the alternative that maximizes their utility. Hence, by investigating people choices, we are able to draw conclusions about their utility, and how the attributes influence this. This assumes that the decisions made by respondents have two components: a deterministic part, specified to capture the role of our explanatory variables (recreation access, cost, etc.), and a random element that we do not capture in our model. This means that the probability of choosing alternative increases with utility. In the case of our CE, a higher level of environmental services provided by NBS would increase the likelihood of the respondent choosing that option. In our interpretation of results, only differences in utilities matter, not overall utility changes. Since we compare with a status quo (business as usual) option and we include a cost attribute, we can employ this approach to determine the willingness-to-pay for co-benefits. This can be phrased in the following way: how much of an increase in cost would our respondents be willing to take in order to accept a decrease in co-benefits, while keeping their utility constant?

5.2 Choice experiment design

5.2.1 Selection of realistic alternatives

One of the key challenges for choice experiments is to reduce the hypothetical bias by showing realistic policies that yield results that are backed by experts and considered realistic by respondents. In this sub-section we show how the information derived from our workshop with local authorities was presented to respondents. It is key that the language used is easy for respondents to understand. Additionally, they should also have a clear picture of how NBS limit flood-risk.

The next step of designing a choice experiment consists in defining alternatives and their attributes. The alternatives are defined as the different options that were presented in the choice experiment.

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Each respondent would have to choose their preferred option from six different choice cards. An example of a choice card can be found in Appendix B. The choice cards show the choices as they are presented to the respondents. They select one of the three alternatives for each choice card that is shown to them. No more than six choice cards were presented to our respondents to avoid cognitive burden. For the same reason, we keep the number of alternatives to only two plus the status quo. The respondents will always be shown two nature-based solutions management plans and one status quo option, where management continues in business-as-usual. Hence, the opt-out option does not cost any additional money per year but also does not provide co-benefits or disservices (loss of agricultural land). It is key that the alternatives, attributes and levels are realistic and, to be useful for policymakers, that they show different scenarios that are currently being considered by local authorities. To do so, we designed an innovation lab session with stakeholders from the region of our case study and representatives from the local government. The following are the main interventions planned, and the ones included in the choice cards.

Table 5.1: Illustration of NbS planned for Limburg and how they reduce flood risk

Reforestation	Involves planting trees to enhance soil stability and water absorption.	
Conversion of agricultural land to natural grassland	Enhances the land's ability to absorb water and store it in the soil.	
Restoring wetlands	Reintroducing natural wetlands that absorb and slow down floodwaters.	
Storage ponds	Temporarily holds excess rain or river water, preventing it from contributing to flooding elsewhere.	

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This information is also presented to the respondents in the same way as in the table above. It is important that the respondents understand the impact that NBS will have on risk-reduction. Similarly, we also introduced the explanation behind the attributes and their levels. Once we have defined our alternatives, we should think about what attributes we should include, and the different levels for each attribute. There are several ways to identify the attributes for a choice experiment. Table 5.2 shows the methods we employed to improve our survey and choice card design for the choice experiment. These are also the main methods identified in the *Handbook of Choice Modelling* (Hess, S. and Daly, A. 2024).

Table 5.2: Roadmap of co-design process for the CE

Method	Date of completion
Review of literature	October 2023
Focus groups with stakeholders (Innovation Lab)	February/March 2024
Expert consultation (KIT)	February – June 2024
Pilot (change if needed)	October 2024

The selected attributes can also be edited if needed according to the results of the pilot survey. In the pilot, we collected 115 respondents as a sample to test if the design is appropriate and the survey is easy to understand. It also helps to improve the experimental design and drop potentially irrelevant attributes since the respondents are asked about which attributes they considered when making choices.

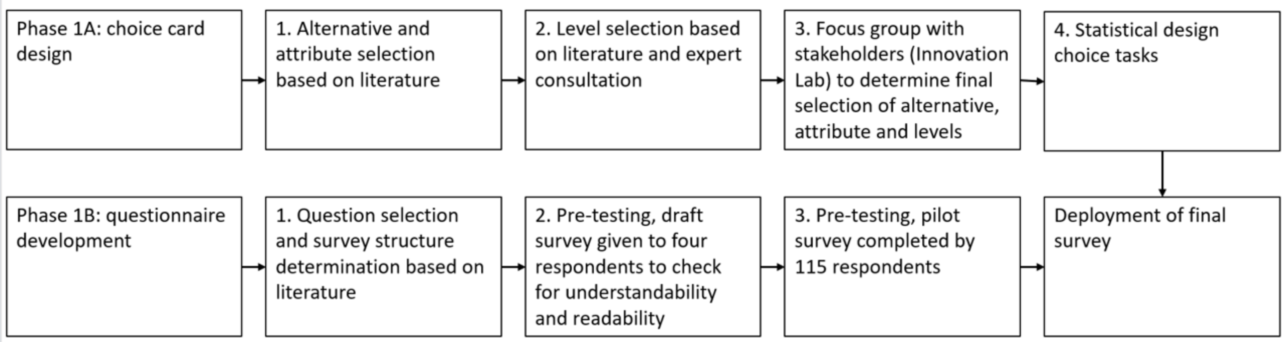

Figure 5.1: Roadmap of Choice Experiment design

5.2.2 Experimental design: Selection of attributes and levels

Identifying the key attributes and levels is one of the main challenges of designing a choice experiment. Particularly, these attributes and levels need to be case-specific, since similar interventions in different contexts could yield different levels of co-benefits. As can be seen in the meta-analysis conducted for the previous deliverable in Work Package 4, several variables impact the valuation of these co-benefits, such as geographical location and income. Additionally, the objective is to fill several gaps in the literature by including some attributes that are traditionally not included in choice experiment analysis for co-benefits of NBS. The meta-analysis allowed to produce a value transfer function that can be used in places where primary data is not available or would be

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too costly to obtain. However, primary data is a better option, when available. There are several shortcomings of meta-analysis, such as the lack of enough evidence with similar characteristics to the policy site characteristics where the value transfer function will be applied

Based on the meta-analysis, we identified several co-benefits that have a statistically significant impact on the valuation of NbS based on over 60 studies and approximately 49,500 total respondents. Recreation and aesthetic appreciation were shown to be associated with higher valuations. In our case, aesthetic appreciation is captured in our "measure" variable, which shows the focus of NBS policies. Additionally, we identified several limitations. Firstly, the case-specific nature of CEs limits their external validity, which can be solved using our value transfer function produced with the meta-regression coefficients. This is particularly relevant since surveys are usually expensive.

Table 5.3: Attributes and levels used in the CE.

Attribute	Levels
Measure	• Agricultural land* • Reforestation • Conversion of agricultural land to natural grassland • Restoring wetlands • Storage ponds
Recreation	• No additional recreational activities* • Non-water related activities • Water-related activities
Biodiversity	• 0 species have their status changed to a favorable status* • 2 species no longer have an unfavorable status • 4 species no longer have an unfavorable status • 6 species no longer have an unfavorable status
Land use change	• No additional conversion of agricultural land for nature-based solutions* • 100 hectares (140 football fields) • 200 hectares (280 football fields) • 500 hectares (700 football fields)
Warning time	• No additional preparation time* • Half an hour • One hour • Two hours
Cost per year	• No additional tax for nature-based solutions* • 10 EUR per year • 25 EUR per year • 50 EUR per year • 100 EUR per year • 200 EUR per year • 300 EUR per year

* Agriculture represents business as usual scenario (opt out)

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Through co-creation, we were able to gather more expert perspectives to determine levels that are realistic and useful for policymaking. Regarding the measures, stakeholders from the municipality highlighted that natural grassland, retention ponds, reforestation and restoring wetlands were the main NBS that were being considered to reduce flood risk. This dialogue with local sources with policymaking insight is crucial so the results of the choice experiment can be used to compare different risk-management strategies. Regarding biodiversity, we consulted how these NBS could have an impact on helping to support current endangered local species.

Additionally, we identified a lack of consideration for disbenefits and land-use considerations, which was also mentioned by our stakeholders from the region. Hence, we included a land use change variable that would capture the potential reluctancy of respondents to change the economic use of current agricultural lands for NBS. The size of the NBS in this attribute is based upon the distribution of size, in hectares, of NBS in the meta-analysis database. We indicate this as a football pitch equivalent to evoke a visual image that most respondents would be familiar with.

Additionally, we include the cost attribute, which is needed to inform the tradeoffs and to derive the willingness-to-pay. The range was chosen based on the Water board tax to ensure realism but also sufficient variation. The last level (300 EUR) is substantially higher – more than 200% increase – than current waterboard tax levels, but it is intended to capture those respondents whose utility curve includes a very high payment for NBS. During the pilot survey, this also allows us to make changes to further improve monetization of co-benefits since a lot of respondents choosing the upper levels could mean that the scale of our cost attributes is too low, and respondents are choosing 300 EUR when in reality they would be picking an even higher value, hence losing all the differences in the upper level.

Once the alternatives, attributes and levels have been defined according to realistic scenarios and to fit the research question and stakeholders' interests, we employed "ngene"[1] for the experimental design. There are several challenges to overcome when designing a choice experiment. For instance, the cognitive burden of respondents can increase if too many choice cards are shown to the respondents, which can lead to less reliable data. Additionally, the choice experiment design aims to capture the trade-offs inherent to every choice made by the respondent, while still showing realistic values to reduce hypothetical bias. The d-efficient design employed for this CE ensures that the most useful trade-offs are presented to respondents, in order to maximize the information captured in their 6 choices, while limiting the cognitive burden for respondents.

The pilot responses helped to further improve the design, for example, by expanding the range in attributes such as cost, in the case most respondents choose the upper limit. Another potential change in design that can arise from the pilot is that some attributes' coefficients may have an opposite sign, which means that we need to scan again for dominant alternatives. This could happen with land use change, whereas there is sufficient evidence in the literature to suggest that the environmental co-benefits should have a positive coefficient, whereas the cost coefficients most likely will show a negative one.

[1] ChoiceMetrics (2012) **Ngene** 1.1.1 User Manual & Reference Guide, Australia

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5.2.3 Survey design

The questionnaire was designed in parallel to the choice experiment design. It was first finalized in English before being translated to Dutch by a native speaker for distribution. This section will show how the survey was structured and the rationale behind the questions that were included in the survey. With the design of the survey, we improve upon existing choice experiment surveys through several new additions. First, we distribute the survey nationwide, instead of focusing solely on the area that was recently impacted by floods. The number of respondents from the region that was recently hit by severe floods (Limburg) is still sufficient to conduct sound statistical analysis, but we are also able to assess how the valuation of co-benefits varies from region to region based on how exposed the respondents are to flood-risk. At future stages, we will also assess if this recent experience also impacts their WTP. While using the whole sample, this could lead to lower estimates for WTP, as we are not only targeting households that suffered floods recently. However, the flood risk is present in several regions of the Netherlands, so other respondents that are not in the Limburg region are also exposed to flood risk. Respondents may also place value of the provided co-benefits, even though they may not directly benefit from the risk-reduction resulting from the NbS. Additionally, based on the input from the municipality of Valkenburg aan de Geul, we avoid a common issue with choice experiments which is the lack of specific context. The NBS that we explain to the respondents in the survey are currently being considered by policymakers, which makes this study policy relevant. The introduction of the survey addresses these issues and reduces the hypothetical bias, since the respondents are informed that their answers are linked to actual plans for flood-risk management.

Another key aspect of this study is the theoretical background. To complement the analysis, we add questions related to protection motivation theory, which aims to explain the factors behind adaptation behavior (Rogers, 1983), as well as environmental attitudes (Dunlap et al., 2000) and preferences for redistribution and equity (Alesina & Giuliano, 2011; Müller & Renes, 2020). This will allow for a richer understanding of preferences for NBS and what factors drive WTP and ultimately influence policy support. The social dimension is usually missing in prior CE studies, which we address by including questions regarding views on fairness, responsibility and the role of the state in terms of redistribution. These answers, combined with the distance to a river or risky area, can help us to assess to what extent policies funded at national level, or solidarity-based insurance systems, could be received by those households that do not live in high-risk areas.

The first set of questions focuses on how the respondent reacted to the choice cards. Here, we aim to identify protest responses or co-benefits that are systematically ignored by our respondents when making their decisions. The protest responses were identified as those of respondents who reject the choice experiment completely, which is different than having a preference for the status quo. The follow-up section is then divided into two main parts. The first set of questions are about risk perception and trust in NBS, based on protection motivation theory literature (Rogers, 1983). We also include a 15-statement framework, namely the New Environmental Paradigm (NEP) scale to test their environmental beliefs, which can influence their willingness to invest in nature restoration policies, such as NBS.

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The second part of the follow up questions focuses on the social dimension of risk and preferences for NBS, of which there is very few empirical studies. This is done by adding questions about their preferences for equity, redistribution and the role of the government in protecting low-income households. Additionally, since we have respondents across the Netherlands, we test to what extent those households that do not live in risky areas are willing to contribute to reducing the risk of high-risk areas. This can be very relevant for public policies and insurance schemes to promote NBS in the future. Lastly, we assess their time preferences and risk aversion. These two variables can also help to predict the respondent's willingness-to-pay for NBS and adaptation measures. First, the inherent lag to perceive some benefits of NBS can lead to those respondents who value the present highly to undervalue NBS benefits. On the other hand, risk averse individuals could also be more likely to invest in adaptation measures or, in this case, be willing to accept a higher tax to increase warning time. Lastly, we include a standard socio-demographics section.

5.3 Illustration of monetization of co-benefits of NbS

Based on the results of the pilot, the final version of the questionnaire and choice experiment was deployed in December 2024. The pilot study consisted of 115 respondents, whereas the final version of the survey obtained more than 2,000 responses. Of these respondents, 10% of the population was from Limburg. This oversampling will allow us to have a large enough sample size to analyze how the recent impact of the floods in Limburg could influence respondent preferences. The majority of the respondents of the pilot study stated that they took all attributes into account, and the open-ended willingness-to-pay question supported the cost range used for its corresponding attribute. Similarly, the pre-test respondents stated that the survey was easy to understand. The priors for the final analysis were updated in ngene, based on the regression coefficients from the multinomial logit attribute-only model. The final dataset was received in January 2025.

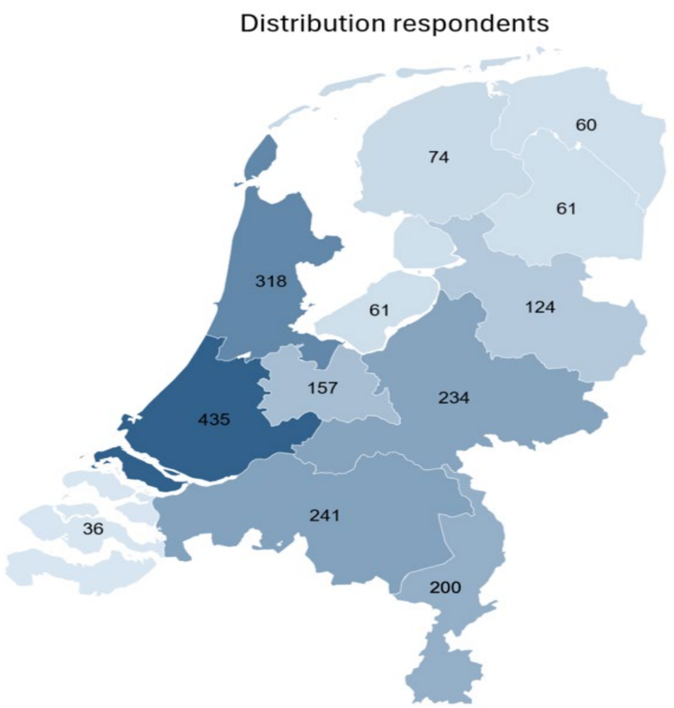

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Figure 5.2: Distribution of respondents across the Netherlands

5.3.1 Descriptive statistics

First, we test whether our sample is representative of the population that we are aiming to study in this research. This is important if we want to infer lessons from our results besides our respondent sample. To do so, we plot the main demographic variables against the distribution in the Netherlands. Our gender distribution is in line to national average: 49.4% of males among our respondents, compared to 49.7% of males at the Dutch level (Statistics Netherlands, 2023). The average age in our sample is higher than the national average by approximately 8 years, which can be explained by the lower limit of 18 years old to be able to fill in the survey.

The income distribution of the sample resembles the distribution of Dutch households. The sample distribution is similarly shaped, with a peak of the average of 30,000 euros annually. Since the income question was structured with bins, this is the 2,000 to 3,000 EUR net monthly income after taxes option, selected by 393 respondents. Our upper-bound bin explains the difference in the right-hand tail of the distribution, as the official Netherland Statistics distribution has a higher concentration of income over 100,000 EUR per year (Netherland Statistics,2023).

Insights into decision-making and protest answers

Once we have assessed the representativeness of our sample, we delve into the decision-making process of the respondents. For instance, we are interested in checking whether our respondents did not take some attributes into consideration when making their choices. 806 respondents stated that they considered all attributes when making their choices, whereas 1,001 considered some attributes only. The remainder of respondents (9%) selected “I don’t know” or they stated their choices were not related to the attributes. We find that all attributes were considered relatively important for our respondents. The question asks respondents to rank all attributes from most important to least important. Particularly, the type of NbS and its role in improving local biodiversity were ranked the highest in terms of importance (2.8 on average), whereas recreation and warning time were the two ranked the lowest (4.2 on average).

266 respondents always selected the opt out option. In order to identify so called protest responses we included debriefing questions to understand the underlying motives behind the answers (Meyerhoff & Liebe, 2010). The reasons for continuously choosing the opt-out option were varied, but the majority of the respondents indicated that they did not want it to be funded through taxes and that the responsibility on investing in adaptation should not be theirs. Around 70% of the respondents indicated that we provided enough information to make informed choices. 25% of the respondents think that we overestimated at least one co-benefit of NbS. Interestingly, the most selected attribute was land use change. In other words, respondents are of the impression that less space is required for nbs.

Social dimension: Views on solidarity for funding adaptation

One key element of NbS policies relates to how these benefits are distributed. NbS can also serve as a tool that protects more vulnerable households that may not have the means to adapt. Additionally, several co-benefits can boost the economic outlook of a region, providing new jobs in

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the tourism sector, etc. In our survey, we found that our respondents think that low-income households are those who benefit the most from NbS. However, if the decision of where to invest in NbS is driven purely from an approach that aims to reduce the damage to assets, this can lead to a lack of protection of lower-income regions with less valuable assets. When asked the question on who the government should prioritize in protecting when investing in NbS, over 55% of the sample indicated that the investment should be done based on purely on risk. Only 360 respondents indicated that higher value areas should be prioritized, whereas 291 indicated that low-income households should be the main priority for the government.

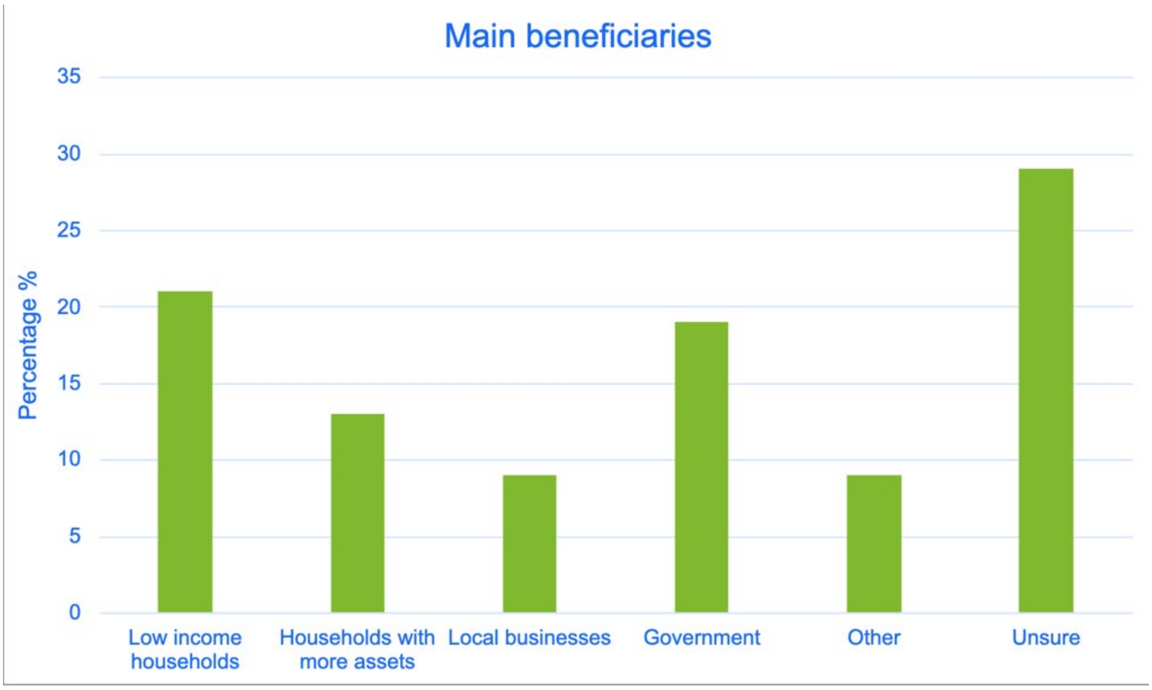

Figure 5.3: Who are the main beneficiaries of NbS?

We delved further into this issue by directly asking who should be responsible for funding flood adaptation measures such as NbS, as shown by Figure 5.4. Despite almost 30% being unsure about who benefits from NbS, less than 40 (<2%) selected that they were unsure about who should be responsible for paying. The national government was chosen by almost 74% of respondents, by a wide margin being identified as the main entity responsible for paying for NbS. This aligns with reality, as 86% of global capital for NbS comes from the public sector. In the Netherlands, the three top answers align with the actual responsible entities for flood protection since water boards and provinces are next, and households are barely chosen by 10% of respondents, which could indicate lower willingness-to-pay when we get to our choice experiment. On the other hand, we find a high degree of stated solidarity for sharing the burden of adaptation among households. 52% of the respondents said that they either agreed or stronger agreed that all households in the Netherlands should share the burden of higher taxes to implement flood protection measures in risky regions, while only 5% strongly disagreed.

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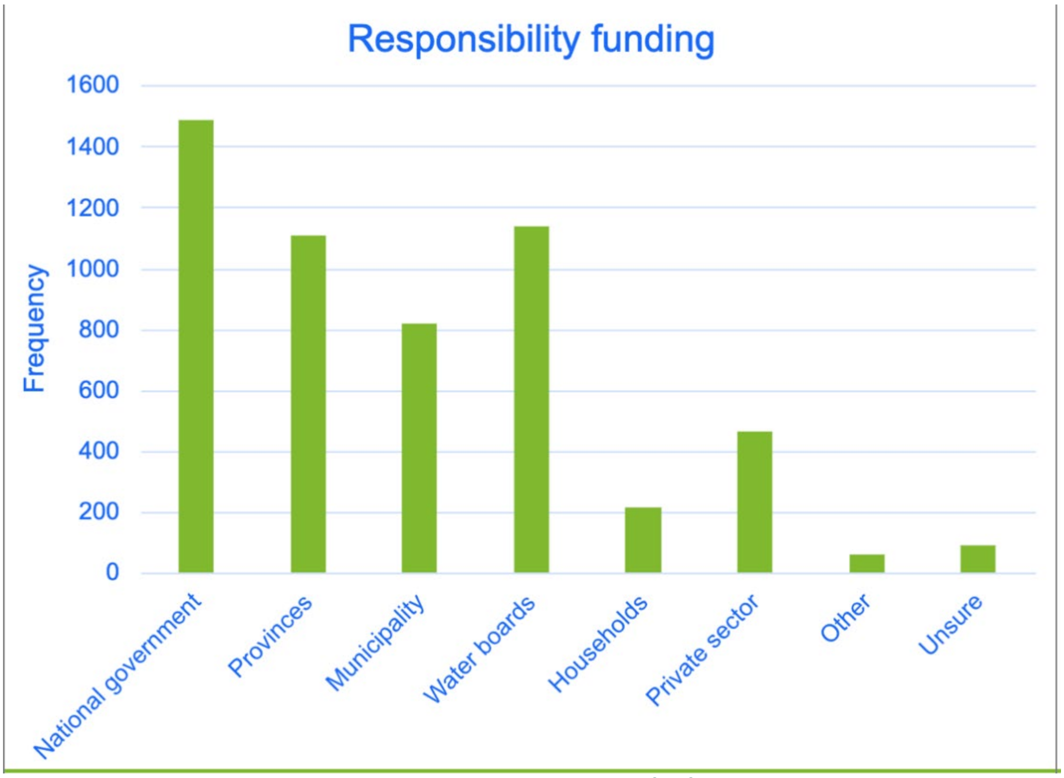

Figure 5.4: Who should be responsible for funding NbS?

5.3.2 Model specification

The data received from the panel provider had to be reformatted specifically so it could be analyzed correctly with the NLogit software package, which requires long formatting of the data. In the process, we also recode the variables when necessary for the model estimation. In all of our model specifications, some attributes were considered linear, whereas others were recorded as dummy variables due to the nature of the levels. For example, the types of NBS solution were initially coded as 1 through 4, where 1 equals retention pond, etc. Hence, we cannot treat this as a continuous variable and was recoded as a dummy variable. The same was done with recreation. In order to have coefficients that are easier to interpret, we created a new variable for land use change, which is just the original variable divided by 1000. This will change the interpretation, as now the WTP indicates how much extra they are willing to contribute per month for each 1000 hectares converted to NbS. A more detailed description of how the key variables were coded can be found in Appendix D.

Among the most common models to analyze CE data are the multinomial logit (MNL) and the Mixed Logit (ML) model. In this case, we add our MNL results in Appendix E, while we focus on the ML results in the next section of the deliverable. This is because ML has become the preferred method in CE literature due to its ability to address certain limitations of MNL (McFadden et al., 1977), such as the assumption of independence of irrelevant alternatives which implies that the relative probability of choosing one option over another remains unchanged when a new alternative is introduced. This assumption is not very realistic where unobserved preference heterogeneity among individuals can lead to correlated choices. The ML model relaxes this assumption by allowing coefficients to vary across individuals, capturing preference heterogeneity through random

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parameters drawn from a specific probability distribution (Hess et al). Our modelling approach follows the Random Utility Theory (McFadden, 1973), which assumes that individuals select the alternative that maximizes their utility:

$U_x = V_x + \varepsilon_x$

The formula shows that Utility of an alternative x, is represented by a systematic component (Vx), which is determined by the observed attributes and a random error term (εx). In the ML model, the probability of choosing alternative i is determined by a distribution of random parameters. Both our MNL and ML models will have utility functions determined only by the attributes of NbS:

$U_{in} = (\beta NbStype * NbStype) + (\beta LandUseChange * \text{Land use change}) \ldots + (\beta Cost * Cost) + \varepsilon_{in}$

The utility of the optout is captured by the alternative specific constant since all the other coefficients are zero for the output. The main difference in the utility functions is that in the MNL model, all coefficients are fixed across individuals, whereas in the ML model these coefficients are random, drawn from a distribution, allowing to account for individual preference variation and correlation of error terms. The results of the MNL in the appendix will be used as a sensitivity test to check whether our results are consistent across different methods. The results of the next section show the ML attribute-only model.

5.3.3 Mixed Logit Results

Table 5.4 shows that reforestation and retention ponds seem to be preferred to the excluded baseline, which is wetlands. The transition to grassland, on the other hand, is not statistically significant. These results are insightful since, in the risk reduction section of this report, we have seen how effective reforestation can be in order to reduce flood risk. This could indicate the viability of reforestation as a technique that would have potential policy support and willingness to contribute to and be effective against climate risk. As expected, biodiversity enhancement, additional warning time and recreation also increase respondents' utility. In the next section, we explore how this translates into a monetary value.

We also find that land use change shows a negative coefficient and is statistically significant at 1% significance level. This indicates that, the more hectares that are converted from agriculture for the development of NbS, the lower the utility of our respondents. This is a particularly important finding for policymaking, as it could influence the policy support from residents. Respondents in the Netherlands place a significant value to the agricultural land, as it is a key part of Dutch culture and landscape, but the alternatives to develop NbS are scarce. This can pose significant problems for public entities to change the economic use of agricultural land for adaptation purposes.

Table 5.4: Mixed Logit Attribute-only model results

Variable	Coefficient	Standard Error	z-value	Prob > |z|	95% CI Lower	95% CI Upper

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Grassland	0.0376	(0.0445)	0.84	0.3981	-0.04967	0.12496
Reforestation	0.3410***	(0.0435)	7.85	0.0	0.2558	0.42612
Retention ponds	0.2955***	(0.0430)	6.87	0.0	0.21127	0.37983
Alternative Specific Constant (Wetlands)	-1.8563***	(0.1290)	-14.39	0.0	-2.10919	-1.60345
Land use change (per 1000 ha)	-0.2353***	(0.0692)	-3.4	0.0007	-0.37102	-0.0996
Recreation (including water activities)	0.0679*	(0.0350)	1.94	0.0523	-0.00066	0.13638
Recreation (no water activities)	0.1343***	(0.0343)	3.92	0.0001	0.0671	0.20158
Biodiversity	0.1023***	(0.0063)	16.16	0.0	0.08988	0.11469
Warning time	0.1369***	(0.0179)	7.65	0.0	0.10184	0.17202
Cost (year)	-0.0049***	(0.0001)	-33.48	0.0	-0.00515	-0.00458

Note: *** $p<0.01$, ** $p<0.05$, * $p<0.10$

5.3.4 Willingness-to-pay estimates

The willingness-to-pay is an economic measure that represents the maximum amount of money that a certain individual is willing to sacrifice to obtain a specific good or service, or improvement in an attribute. In this case, we estimate how much they are willing to pay each month for each attribute of NbS. The WTP is estimated from the results of the ML regression showed in the previous section. This is done by dividing the estimated coefficient of a particular variable by the cost coefficient. This ratio expresses how much you can increase the quantity or quality of a service while also increasing the cost, in a way that total utility remains constant. A positive WTP indicates that respondents positively value a certain attribute, whereas a negative WTP suggests that respondents associate disutility to that attribute and that they would require compensation instead.

$$WTPj = -\beta j \ / \ \beta cost$$

where:
WTPj = Willingness to pay for attribute j (i.e. increase in monthly tax)
Bj = Estimated coefficient for attribute j in the ML model
Bcost = Estimated coefficient of the cost variable

Table 5.5. shows the estimates per hectare per year for each type of NbS. Our values are in line with previous studies in Limburg (Robinson et al, 2022). We can see that reforestation has the highest value, followed by retention ponds. This yearly WTP would increase per year if the NbS allows for recreational activities. This shows how much respondents value being able to use the green spaces,

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which should also be considered in policymaking since also studies have found that accessible nature in the surroundings increases life satisfaction and wellbeing (de Vries et al, 2023). Increasing warning time by 30 minutes would increase WTP of the NbS per hectare per year by 0.37 EUR per respondent, whereas biodiversity would increase the WTP by 0.36 EUR per respondent. To estimate the value of the NbS, we should consider the number of affected households, the co-benefits and its size.

Table 5.5: WTP per hectare per year

	Grassland	Reforestation	Retention ponds	Wetlands
No recreation / Base value (per ha per year)	0.341	0.404	0.394	0.382
Recreation (no water) (per ha)	0.710	0.835	0.816	0.791
Recreation (including water)	1.093	1.280	1.252	1.215
Only 30 min of warning	0.710	0.835	0.817	0.792
Only biodiversity	0.703	0.828	0.810	0.785

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6 Discussion

In this deliverable, we build upon the previous review (Deliverable 4.1) and stock-taking of current methods to assess the risk-reduction benefits and societal co-benefits of NBS. First, we co-created the new metrics and methods with relevant stakeholders by asking their needs, the current problems they were facing in their specific roles and, for our case study in Limburg, which NBS have been planned. Then we introduced the case study and illustrated our improved methods in the previous sections. At the end of each section, both for risk-reduction and co-benefits, we show the results applied to the case study.

Through the co-creation process, we addressed several issues in current NbS benefit assessment. From the risk-reduction-side, the newly developed catastrophe risk model presents accounts for the impact on hydrological conditions and flood risk of potential NbS planned for the region of Limburg. Based on the results of Deliverable 4.1, we identified the lack of consideration for potential disbenefits, which was addressed in this choice experiment. Local stakeholders' views were also taken into account in the design of the choice experiment during the Innovation Labs. These allowed to select NbS that are being considered for the region of Limburg, hence increasing policy relevance.

These results can provide valuable insight into flood risk management in the region of Limburg. On the one hand, the object-based model shows how much the risk-reduction performance can vary from one NbS to another. Reforestation proves to be very effective in reducing the expected damage regardless of the return period. It is also a cost-efficient measure, with a benefit-cost ratio of 1.06. On the other hand, storage ponds may need the co-benefit monetization for it to become an attractive investment, as its performance is weaker. This is partly due to its limited capacity to store water: once the ponds are full, they won't be able to keep reducing the flood risk further, making them less effective for less frequent and more intense flooding.

These results are also important for insurance. Through risk-based premiums, the reduction in risk can improve insurability, closing the insurance gap and resulting in new customers for insurance companies. Closing the insurance gap also creates stability for more vulnerable households that could find more difficulties in recovering from a severe flood. Hence, NbS could also have social benefits besides the co-benefits.

The risk-reduction results can be coupled with the co-benefits monetization through tools such as social cost-benefit analysis or multi-criteria decision analysis. Our newly developed choice experiment showed valuable insight regarding people's preferences for NbS. The willingness-to-pay estimates can inform decision-makers regarding potential policy support for policies funded through higher taxes. Respondents seemed to be willing to pay for co-benefits such as recreation or biodiversity enhancement, which is standard in literature. Additionally, reforestation and retention ponds were preferred options over wetlands and grassland. However, we found our respondents reluctant to give up agricultural land for NbS. This is an important finding since it could signal resistance from the population in case these NbS are developed in agricultural land. This poses a key challenge in the case of reforestation since it needs more hectares to be converted from agricultural land, but it has also been estimated to be very effective in reducing flood risk and is the preferred NbS as indicated in our mixed logit model.

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In the next phase of the project, in deliverable D4.3, we will build upon these results and focus on financing of NbS. We will explore financing strategies for both the private and public sector. We will identify beneficiaries in order to design these schemes in a way that is attractive for all involved actors. We will analyze the potential impact of NbS on premiums and insurability, combined with their multiple co-benefits, in order to assess whether investment in NbS can be an attractive investment for the private and public sectors.

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8 Appendices

8.1 Appendix A: Innovation Lab description

Indicator	Session 1	Session 2	Session 3
Organisations involved	Dutch Association of Insurers, Achmea, Rabobank, Ministry of Finance, IVM	ASR, Dutch Association of Insurers, Achmea, Rabobank, IVM	Municipality of Valkenburg aan de Geul, Dutch Association of Insurers, Ministry of Infrastructure and Water Management, IVM
Experts participating (#)	40	14	10
Main topic of discussion	Defining the challenge; Introduction to the Innovation Lab objectives.	Discussion on new flood-risk models developed at IVM and how they can be used by insurers.	Focused on the choice experiment that will be deployed in September, particularly on measures designed for Limburg and what attributes (characteristics) are relevant for stakeholders.

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8.2 Appendix B: Choice card

	Nature-based solutions policy 1	Nature-based solutions policy 2	Policy without nature-based solutions
Recreation	No additional recreational activities	Water-related activities	No additional recreational activities
Biodiversity	6 species no longer have an unfavourable status	4 species no longer have an unfavourable status	No change in habitat status
Conversion agricultural land	100 hectares	100 hectares	No additional conversion of agricultural land
Evacuation time	2-hour evacuation time	1-hour additional evacuation time	No additional warning time
Measures	Focus on forestation	Focus on grassland	No nature-based solutions
Cost	50 euro's	50 euro's	No additional cost
Which would you choose?	◯	◯	◯

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8.3 Appendix C: Full Survey – English Version

1. Survey introduction

Dear participant,

This survey is conducted by the Vrije Universiteit Amsterdam to gather information about the preferences for different natural solutions against flooding. Your answers will inform policymakers about preferences for flood risk management, which is a key policy issue.

Participation is completely voluntary, and you may decide to end your participation at any time without giving any reasons. The survey will take approximately 15 a 20 minutes.

Your privacy will be protected in accordance with the General Data Protection Act (AVG) and the General Data Protection Implementation Act (UAVG). No personally identifiable information will be reported in the research products. The data will be archived for at least 10 years for scientific integrity. The data may be re-used in future research projects. For more detailed information, please see the link below:

Privacy_verklaring

In case of any questions about the research, please contact (g.garcia.alvarez@vu.nl). In case of any question regarding privacy please contact the Data Protection Officer of VU Amsterdam (functionarisgegevensbescherming@vu.nl)

We hope we have provided you with sufficient information and thank you in advance for your participation in this study.

I hereby declare that I have read the information provided in the above. I consent to participate in the survey and have my data processed in accordance with the terms described above.

- Yes
- No (end of survey)

2. Preliminary questions

Question 1:
How far is your home from the nearest river or stream?

- Less than 1 km
- Between 1 km to less than 2 km
- Between 2 km to less than 5 km

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- More than 5 km
- I don't know

Question 2:
How would you describe your neighborhood regarding the amount of green/blue?

- An area without green and/ or water
- An area with some green and/or water
- An area with abundant green and/or water
- I don’t know

Question 3a:
How would you rate the availability and quality of nature-related recreational options (e.g., parks, hiking trails, rivers) near your home?

- Very poor
- Poor
- Average
- Good
- Excellent
- I don’t know

Question 3b:
How would you rate the availability and quality of nature-related recreational options (e.g., parks, hiking trails, rivers) near your home?

- Very poor
- Poor
- Average
- Good
- Excellent
- I don’t know

3. Information flood measures

In July 2021, several European countries, including the Netherlands, experienced unprecedented flooding, resulting from intense rainfall that led to rivers bursting their banks. This event caused significant damage and highlighted the need for improved flood risk management strategies in Limburg and other parts of the Netherlands.

Insert picture

Limburg, 2021

Currently flood risk is mainly managed through technical solutions, such as the construction and maintenance of dikes. These measures can be extended with nature-based solutions that reduce flood risks. Examples include restoring wetlands and natural floodplains, which can absorb rainwater, and reforesting watersheds to slow the rate of water entering rivers. Nature-based solutions also provide additional benefits such as biodiversity conservation and providing areas for recreation. A disadvantage

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is that currently used land might need to be given up for nature-based solutions. Furthermore, it can take years to realize the effectiveness of some nature-based solutions.

4. Attribute explanation

Read the following carefully before continuing with the questions.

Next, you will be asked to choose between three different policies to limit flood risk caused by heavy rainfall: two options with nature based solutions and one without nature based solutions. The policies are designed to be implemented next to the nearest river or stream from your house of residence. You are asked to pick your preferred policy considering their characteristics and the extra implementation cost. Based on their design, nature-based solutions can change recreation, biodiversity, land use, evacuation time and costs to varying extents.

The next page explains the different characteristics.

Type of nature-based solution:

The first characteristic of a policy refers to the type of nature-based solution that would implemented, which are shown below.

Reforestation	Involves planting trees to enhance soil stability and water absorption.	
Natural grassland	Enhances the land's ability to absorb water and store it in the soil.	
Restoring wetlands	Reintroducing natural wetlands that absorb and slow down floodwaters.	
Storage ponds	Temporarily holds excess rain or river water, preventing it from contributing to flooding elsewhere.	

In the policy of no additional nature-based solutions the current land use will remain agriculture land.

While the policy will prioritize one specific measure, additional nature-based solutions may also be implemented, although they will only constitute a small percentage of the overall strategy.

Required agricultural land

The following characteristic refers to the conversion of agricultural land to implement nature-based solutions. These measures would be implemented on land that currently serves another purpose, in this case agricultural land. If no agricultural land is converted, the measures will be implemented on land with uses other than agriculture.

The policy options can include four levels of land use change: no conversion of agricultural land for nature-based solutions, 100 hectares (140 football fields), 200 hectares (280 football fields) or 500 hectares (700 football fields).

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Recreation:

Whereas agricultural land is inaccessible for visitors, the proposed land-use changes may be accessed by local visitors for recreational purposes such as cycling or water-related activities.

The policies can include three different levels of recreation: no additional recreational activities, non-water related activities such as hiking and walking, and water-related activities such as swimming and boating.

Biodiversity:

The following characteristic refers to the population conservation status of habitat indicator species. A favorable status illustrates a situation where a species is prospering with good prospects in the future as well, whereas an unfavorable status means this population is threatened.

The policies can include four levels of biodiversity: 0 species, 2 species, 4 species, 6 species no reach a favorable status.

Example of four habitat species with an unfavorable status. From top left to bottom right: Hazelmuis, Geelbuikvuurpad, Muurhagedis, Brandts vleermuis.

Additional warning time:

The following characteristic refers to additional warning time during extreme rainfall that could lead to flooding. While the likelihood of flooding can be reduced, it cannot be completely eliminated. As such, warning systems notify exposed populations of an upcoming flood to allow people to take preparations. Nature-based solutions can slow down high-water levels and floods, resulting in additional time to prepare or evacuate after heavy precipitation.

The policy options can include four levels of additional preparation time: no additional preparation time, half an hour, hour or two hours of additional preparation time.

Yearly increase waterboard tax

The cost refers to the yearly increase of the waterboard tax per household that is earmarked for the implementation of nature-based solutions. Based on the design of the policies, the waterboard tax will have to be increased by either €10, €25, €50, €100, €200 or €300 per year.

5. Explanation choice experiment

If you choose neither of the nature-based policy scenarios, then no nature-based solutions in addition to the current grey flood measures will be implemented. Instead, flood risk management will continue its current strategy of implementing technical solutions such as dykes to reduce flood risk. While both types of measures result in the same levels of flood risk reduction, the policy without nature-based solutions creates no additional benefits for recreation, biodiversity and evacuation time.

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We will ask 6 times your preferences for different policies. Please choose your preferred policy each time independently of the choice previously made.

Please choose your preferred policy for managing flood risk in the nearest river basin from your house of residence.

6. Follow-up questions CE

Question 4:
(If always status quo)

You have selected the policy without nature-based solutions every time. Could you indicate why?

- My household cannot afford it
- I am not confident that the money will be used as specified
- I don't believe that flooding is a problem in my region
- I am against higher taxes in general, no matter what it is used for
- I should not be the one paying for flood management measures
- Other (please specify)
- Don't know / Prefer not to answer

Question 5a:
How did you make your choices?

- Considering all 6 characteristics simultaneously
- Only considering certain characteristics
- Choosing the options randomly

Question 5b:
(If only considering certain characteristics)
Can you indicate which characteristics you considered?

- Type of nature-based solution
- Required agricultural land
- Recreation
- Biodiversity
- Additional warning time
- Yearly increase waterboard tax

Question 6:
(Pre-test question) Did you consider we provided enough information about the measures to make informed choices?

- Yes, the information was sufficient.
- Yes, the information is excessive.

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- No, I don't think I had enough information to make informed decisions.
- I don't know.

Question 7:
(Pre-test question) If the current yearly waterboard tax would be increased to fund nature-based solutions, what is the maximum you would be willing to pay per year to implement the measures shown in the above scenarios?
(Open ended)

Question 8:
Do you consider that the benefits of the proposed measures are realistic?

- Yes, I think the benefits shown are realistic.
- No, I think the benefits shown are an overestimation
- No, I think the benefits shown are an underestimation
- I don't know.

Question 8b (if no to previous answer):
If you selected "no" in the previous question, to which benefit were you referring?
- Type of nature-based solution
- Required agricultural land
- Recreation
- Biodiversity
- Additional warning time
- Yearly increase waterboard tax

Question 9:
Could you rank the characteristics based on how relevant they were for you when making your choices, from most important (1), to least important (6)?

- Type of nature-based solution
- Required agricultural land
- Recreation
- Biodiversity
- Additional warning time
- Yearly increase waterboard tax

Question 10:
How effective do you think the measures shown in the choice cards are in reducing flood risk for the nearest river basin from your house of residence?

	Not effective at all	Not very effective	Effective	Very effective	I don't know
Reforestation					
Natural grass					

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Restoring wetlands					
Storage ponds					

Question 11:
How difficult do you think it would be for the government to implement these nature-based solutions to reduce flood risk?

	Very difficult	Difficult	Easy	Very easy	I don't know
Reforestation					
Natural grass					
Restoring wetlands					
Storage ponds					

Question 12:
How high do you personally estimate the costs of implementing nature-based solutions to reduce flood risk, in terms of money and time investment?

	No high costs at all	Not such high costs	High costs	Very high costs	I don't know
Reforestation					
Natural grass					
Restoring wetlands					
Storage ponds					

Question 13:

Please indicate to what extent you agree with the following statements:

	Totally disagree	Disagree	Neither disagree nor agree	Agree	Totally agree
We are approaching the limit of the number of people the Earth can support					
Humans have the right to modify the natural environment to suit their needs					

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When humans interfere with nature it often produces disastrous consequences					
Human ingenuity will ensure that we do not make the Earth unlivable					
Humans are seriously abusing the environment					
The Earth has plenty of natural resources if we just learn how to develop them					
Plants and animals have as much right as humans to exist					
The balance of nature is strong enough to cope with the impacts of modern industrial nations					
Despite our special abilities, humans are still subject to the laws of nature					
The so-called "ecological crisis" facing humankind has been greatly exaggerated					
The Earth is like a spaceship with very limited room and resources					
Humans were meant to rule over the rest of nature					
The balance of nature is very delicate and easily upset					
Humans will eventually learn enough about how nature works to be able to control it					
If things continue on their present course, we will soon experience a major ecological catastrophe					

7. Follow-up questions redistribution / insurance

Question 14:
Who do you think should be responsible for funding flood adaptation measures such as nature-based solutions? (tick all that apply)

- The central government
- The provincial government
- The municipal government

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- The waterboards
- The affected community
- Private sector (insurers, project developers)
- Other, namely
- I don't know

Question 15:
Who do you think are the main beneficiaries of the policies stated in the choice cards?

- Low income households in the region
- Wealthier households that own more assets in the region
- Local businesses
- The government
- Other, namely
- I don't know

Question 16:
What do you think the policymakers should prioritize when implementing flood management strategies such as the displayed in the choice cards?

- Protecting low-income households
- Protecting the areas there the economic damage to assets would be greater
- Protecting households located in the highest risk areas
- Other, namely
- I don't know

Question 17:
To what extent do you agree with following statement: "All households in the Netherlands should share the burden of higher taxes to implement flood protection measures in regions with higher risk"

- Strongly disagree
- Disagree
- Neither disagree nor agree
- Agree
- Strongly agree
- I don't know

Question 18:
To what extent do you agree with the following statement**:** "I think the local communities should be involved in the decision-making process of flood management policies"

- Strongly disagree
- Disagree
- Neither disagree nor agree
- Agree
- Strongly agree
- I don't know

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Question 19:
To what extent do you agree with the following statement: “The government should take more responsibility to ensure that everyone is provided for, including protecting those who decide to live in riskier areas”

- Strongly disagree
- Disagree
- Neither disagree nor agree
- Agree
- Strongly agree
- I don’t know

Question 20:
Money can be distributed over 2 people in different ways. Below four proposals (A, B, C and D) on how to distribute money between person 1 and person 2 are depicted. We kindly ask you to indicate which of these alternatives you prefer.

- Alternative A: person 1 receives €10; person 2 receives €9 (19 Euros total)
- Alternative B: person 1 receives €15; person 2 receives €7 (22 Euros total)
- Alternative C: person 1 receives €8; person 2 receives €8 (16 Euros total)
- Alternative D: person 1 receives €16; person 2 receives €2 (18 Euros total)

Question 21:
To what extent do you agree with this statement: “The government should take measures to reduce income differences”. Keep in mind that these measures might be financed by taxes that would lead to reductions in one’s salary.

- Strongly disagree
- Disagree
- Neither disagree nor agree
- Agree
- Strongly agree
- I don’t know

Question 22:
From the following list, check the 4 areas that you think are most important and for which the State should invest more money. Then rank them in order of priority from 1 to 4.

- Education
- Unemployment and social security
- Housing crisis
- Aid to poor countries
- Migration
- Climate and the environment
- National defense
- Crime and justice
- Local economic development
- Health

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- Flood-risk defense
- Other, namely

8. Follow-up questions flood risk

Question 23a:
To what extent do you agree with the following statement: “I think the flood protection levels are sufficient in the area where I live to protect me from floods.”

Flood protection levels refer to the he average probability of flooding of surface water per year

- Strongly disagree
- Disagree
- Neither agree nor disagree
- Agree
- Strongly agree
- I don't know

Question 23b:

Flood protection levels refer to the he average probability of flooding of surface water per year

- 1 in 10 years
- 1 in 25 years
- 1 in 50 years
- 1 in 100 years
- 1 in 250 years or ...
- Other, namely
- I don’t know

Question 24:
Did you experience floods in the last 5 years where water entered your home?

- Yes
- No
- I don’t know

Question 25:
If ‘yes’ question 24

What was the source of the flood water?

- River flooding where a river bursts or overtops its banks
- Excess rainwater flowing overland
- Sewer flooding
- Groundwater flooding as a result of rising groundwater
- Other, namely
- I don’t know

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Question 26:
If “yes” question 24

What is the most recent year in which you experienced a flood where water entered your home? (Open ended question)

Question 27:
Have you taken measures to protect your home or other possessions against flood damage, for example watertight bulkheads or elevating appliances such as boilers and electricity?

- Yes
- No

Question 28:
How likely is it in your opinion that you will be affected by flooding in the coming 5 years, meaning that flood water reaches or enters your home or building?

- Very unlikely
- Unlikely
- Likely
- Very likely
- I don’t know

Question 29:
How many major floods events would have to happen in the upcoming 5 years for you to decide to permanently relocate away from your neighborhood?

- This is not relevant in my decision to relocate
- 1 major flood event
- 2 major flood events
- 3 major flood events
- 4 major flood events
- 5 major flood events
- 6-10 major flood events
- More than 10 major flood events
- I don’t know

Question 30:
To what extent do you agree with the following statement: “The likelihood of flooding is too low to be concerned about the consequences.”

- Strongly disagree
- Disagree
- Neither agree nor disagree
- Agree
- Strongly agree

Question 31:

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To what extent do you agree with the following statement: “I am worried about the danger of flooding at my current residence.”

- Strongly disagree
- Disagree
- Neither disagree nor agree
- Agree
- Strongly agree

Question 32:
Do you expect that the frequency of floods will decrease, increase, or stay the same in your region in the coming 5 years?

- Decrease a lot
- Decrease
- Stay the same
- Increase
- Increase a lot
- I don't know

Question 33:
Do you expect that the severity of floods will decrease, increase, or stay the same in your region in the coming 5 years?

Severity can for example refer to the water level during a flood, or the size of the area that is flooded

- Decrease a lot
- Decrease
- Stay the same
- Increase
- Increase a lot
- I don't know

Question 34:
In the event of an increased risk of flooding due to heavy rainfall, warning messages can be sent to alert and inform residents about the flood risk. How do you assess the reliability of such warnings?’

- Very unreliable
- Unreliable
- Neither unreliable nor reliable
- Reliable
- Very reliable

Question 35:
How much do you trust the ability of government officials to limit flood risk where you live. For example, by maintaining levees?

- Not trust them at all
- Not trust them very much
- Trust them somewhat

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- Trust them completely
- I don't know

Question 36:
To what extent do you agree with the following statements:

	Strongly disagree	Disagree	Neither disagree nor agree	Agree	Strongly agree
I have the resources, time and opportunities to contribute to public flood control					
I consider that my payment would improve the current situation regarding public flood control					
Increasing flood protection levels would be a waste of public money					
Increasing flood protection levels should not be considered by policy makers					
Increasing the flood protection levels will benefit our society					
The people who are important to me think that citizens should pay for public flood control					

Question 37:
In general, are you someone who is willing to take risks, or do you try to avoid risk? Please answer on a 10-point scale, where 0 means you are not at all willing to take risks and 10 means you are very willing to take risks.

Question 38:

When it comes to financial decisions, how willing are you to give up something that is beneficial for you today in order to benefit more from that in the future? Please answer on a 10-point scale, where 1 means that you are completely unwilling, to give up something today and a 10 means you are very willing to give up something today.

Question 39:
Some people feel like they are fully in control of their live, while others feel like they have no control how their life turns out.
Using a 10-point scale, where 0 means you have no control and 10 means you have complete control, what number reflects how much control you think you have over how your life turns out?

9. Demographics

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Question 40:
How old are you (in years)?

- 18-24 years
- 25-34 years
- 35-44 years
- 45-54 years
- 55-64 years
- 65 years or older
- Prefer not to say

Question 41:
With which gender do you identify most?

- Male
- Female
- Other
- Prefer not to say

Question 42:
In what type of housing do you live?

- Apartment
- Studio
- Maisonette
- Row house
- Semi-detached
- Detached
- Bungalow
- Houseboat
- Other, namely:
- Prefer not to say

Question 43:
Do you own the place where you currently reside?

- Yes
- No, I am a tenant
- Other
- Prefer not to say

Question 44:
How long have you already inhabited the house you currently live in (in years)?

Question 45:
Is your house or apartment located on the ground floor?

- Yes
- No

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- Prefer not to say

Question 46:
How many people does your household consist of, including yourself?
- 1
- 2
- 3
- 4
- 5
- 6
- More than 6
- Prefer not to say

Question 47:
How many children below 18 years currently live in your household?
- None
- 1
- 2
- 3
- 4
- 5
- More than 5
- Prefer not to say

Question 48:
What is the highest level of completed education?

- Basisonderwijs (Primary Education)
- VMBO (Preparatory Secondary Vocational Education)
- HAVO (Higher General Secondary Education)
- VWO (Pre-university Education)
- MBO (Secondary Vocational Education)
- HBO (Higher Professional Education)
- WO Bachelor's (University Bachelor's Degree)
- Post-graduate education (Master, PhD...)
- No education completed
- Other
- Prefer not to say

Question 49:
Indicate in which sector you work?

- Environment and Agriculture, Forestry, and Fishery
- Retail and Wholesale Trade
- Information Technology and Telecommunications
- Healthcare and Social Assistance
- Justice, security and public administration
- Media and communications
- Education, culture and science

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- Engineering, manufacturing and construction
- Tourism and hospitality industry
- Transportation and Logistics
- Unemployed
- Retired
- Other (please specify)
- Prefer not to say

Question 50:
What is your household's total net monthly income after taxes?

- Less than €1000
- Between €1000 and €1499
- Between €1500 and €1999
- Between €2000 and €2999
- Between €3000 and €3999
- Between €4000 and €4999
- Between €5000 and €6999
- Between €7000 and €9999
- €10.000 or more
- Prefer not to say

Question 51:
Can you indicate your postcode?
(open question – give the option to provide only the first four digits if the respondent does not want to provide all the six digits)

Question 52:
How easy to understand was the survey for you?

- Very easy
- Easy
- Neither easy nor hard
- Hard
- Very hard
- I don't know

Question 53:
Thank you for your participation. Do you have any further comment regarding the survey?
(Open ended)

END OF SURVEY

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8.4 Appendix D: Coding of key variables

Variable	Description	Coding
Grassland	Dummy variable: 1 if the NbS measure includes grassland restoration, 0 otherwise.	Binary (0/1)
Reforestation	Dummy variable: 1 if the NbS measure includes reforestation, 0 otherwise.	Binary (0/1)
Retention Ponds	Dummy variable: 1 if the NbS measure includes retention ponds, 0 otherwise.	Binary (0/1)
Including Water Activities	Dummy variable: 1 if recreational activities include water-based options, 0 otherwise.	Binary (0/1)
Excluding Water Activities	Dummy variable: 1 if recreational activities exclude water-based options, 0 otherwise.	Binary (0/1)
Biodiversity	Reduction of local species categorized under “unfavourable” status	Continuous
Additional Warning Time	Extra hours of warning time to take measures (evacuation, etc.)	Continuous
Land Use Change (ha)	Hectares that will be reconverted from agriculture to NbS divided by 1000	Continuous
Cost	Increase in waterboard tax (EUR/year)	Continuous
Alternative Specific Constant (ASC)	Alternative Specific Constant (ASC) used to capture unobserved effects in the model.	Intercept

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8.5 Appendix E: MNL results

Variable	Coefficient (SE)	z-value	p-value	95% CI
Grassland	0.05318 (0.03978)	1.34	0.1813	(-0.02480, 0.13115)
Reforestation	0.29654*** (0.03944)	7.52	0	(0.21924, 0.37385)
Retention Ponds	0.26142*** (0.03841)	6.81	0	(0.18613, 0.33671)
Including Water Activities	0.06082* (0.03182)	1.91	0.056	(-0.00155, 0.12319)
Excluding Water Activities	0.12674*** (0.03134)	4.04	0.0001	(0.06531, 0.18816)
Biodiversity	0.09443*** (0.00498)	18.95	0	(0.08467, 0.10420)
Additional Warning Time	0.12755*** (0.01524)	8.37	0	(0.09769, 0.15742)
Land Use Change (ha)	-0.17688*** (0.06084)	-2.91	0.0036	(-0.29611, -0.05764)
Cost	-0.00442*** (0.00012)	-36.27	0	(-0.00466, -0.00418)
Alternative Specific Constant (ASC)	-0.52568*** (0.04697)	-11.19	0	(-0.61774, -0.43362)

Note: *** p<0.01, ** p<0.05, * p<0.10

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8.6 Appendix F: WTP estimates per year per 1000 hectares

Attribute / NbS type	Grassland	Reforestation	Retention ponds	Wetlands
No recreation / Base value	341.29	403.70	394.35	381.96
Recreation (no water)	368.93	431.34	421.99	409.60
Recreation (including water)	382.89	445.30	435.96	423.56
Only additional warning time	369.46	431.88	422.53	410.13
Only biodiversity	362.33	424.74	415.40	403.01

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