1. INTRODUCTION

Extreme weather events (such as floods, heat waves, or droughts) are a pressing global concern due to the devastation that they can cause (e.g., IPCC, 2012). While several types of extreme weather events are worthy of study, this thesis focuses on flooding, which is the most common natural disaster (Swiss Re, 2015) and the one with the greatest effect on humanity (UNISDR, 2011). Munich Re (2015a) shows that 42% of global reported disaster events were floods, causing 24% and 28% of recorded fatalities and monetary damage in 2015, respectively. As an illustration, in May 2015 floods in the United States (U.S.) caused $2.7 billion in damage, while in December of the same year floods across the United Kingdom, Ireland and Norway resulted in $1.6–$2 billion in damage (Munich Re, 2015b; Swiss Re, 2016). Despite these large impacts, 2015 does not appear to have been an outlying year, as from 1990 to 2010 there was an annual average worldwide loss of $23 billion due to flooding (Jongman et al., 2015). Europe as a whole has suffered an annual average loss of $14 billion between 1980 and 2010 due to the effects of extreme weather events (NMI, 2013).

The past impacts of flooding have sparked large-scale actions by governments and citizens to limit flood impacts (see Husby et al., 2014; Benson et al., 2016). Nevertheless, flood preparedness should be improved, because the recent flood events are part of a longer-term upward trend in flood impacts (e.g., Barredo, 2007; Bouwer, 2011). Given the upward trend in natural disaster losses, understanding the potential evolution of flood damages can allow society to better manage and control the actual direction in which flood impacts will move in the future.

The importance of understanding how flood impacts will evolve has led to a great deal of academic work on this topic (e.g., Preston, 2013; Changnon et al., 2000; IPCC, 2012; Milly et al., 2002; Schiermeier, 2011; Jongman et al., 2014; Wimsemius et al., 2016). The studies focusing on Europe have shown a strong trend towards increasing flood damage, with some analyses predicting that costs may triple by 2080 (Alfieri et al., 2015), or even be up to 4 times larger in the 2050s than in 2010 (Jongman et al. 2014), depending on the climate change scenario used. Collectively, these studies show that, across Europe, the threat posed by flooding is increasing due to population and economic growth in flood-prone areas, while climate change alters the probability and extent of flooding (e.g., IPCC, 2012; Kundzewicz et al., 2014; Alfieri et al., 2015; Rojas et al., 2013). While climate change contributes to changing risk profiles in Europe, socio-economic development tends to be the leading contributor, and a somewhat stronger driver in Eastern as compared to Western Europe (Rojas et al., 2013; Wimsemius et al., 2016). The problem of climate change is a global externality, whereas the socio-economic drivers of flood risk may be more easily controlled through improved management of said drivers. Controlling these drivers can minimize future exposure and the vulnerability of people and assets.

The socio-economic development of flood-prone areas is determined by decisions taken by stakeholders: some stakeholders (such as homeowners or property developers) can take actions that increase the potential impact of a flood event, while others (e.g., insurers or land-use regulators) try to promote actions that limit potential flood impacts. The interaction between these stakeholders should be influenced to limit flood risk because it can take a long time to recover from the impacts of flooding and the recovery process can result in a great deal of pressure being placed on the involved stakeholders. For example, the effects of Hurricane Katrina were estimated to take between 8 and 11 years to recover from a monetary loss of $40–$50 billion and over 1,500 fatalities (Kates et al., 2006). The growing pressure on stakeholder budgets makes the minimization of costs of natural disasters a top priority. Preventing direct flood impacts (such as property losses) also prevents substantial indirect impacts, such as business interruptions (Koks et al., 2016), or potentially larger intangible welfare impacts (Chapter 2).

To minimise the effects of natural disasters, active management is required, as noted in the Sendai framework for disaster risk reduction for the period 2015–2030. One of the key priorities of the Sendai framework is to improve societal resilience (Mechler, 2016). While the definition of resilience

is contested (e.g., Klein et al., 2003; Rose, 2007), most definitions tend to focus on recovering from the impacts of a flood event quickly and at a low cost. The Sendai framework, therefore, encourages the use of measures that finance recovery costs, while offering incentives to reduce the potential impacts of flood events (Mysiak et al., 2016).

There are many potential measures that can help meet the goals of the Sendai framework. For instance, flood barriers or levees can be built to prevent flooding (e.g., Aerts et al., 2013). However, some of those measures can be expensive, and often have intangible and tangible benefits that occur over the long term or display the features of a public good. A risk analysis is required to evaluate proposed measures in order to make the best use of limited resources while accounting for uncertainty in the occurrence and impacts of floods (Grossi Kunreuther, 2005). Risk is a metric that converts the continuum of potential impacts into a value that can be used to guide decisions about how to manage flooding. Assessments of risks and risk management measures often follow these steps: evaluating the magnitude of the threat posed; identification of the possible risk reduction measures and costs; an effectiveness analysis of these measures; and finally calculation of economic efficiency of risk reduction measures (Mechler, 2016). However, while monetary values of risk or impacts are suitable metrics for guiding risk management decisions, they may be even more useful as inputs into a broader analysis of the objectives and consequences of flood insurance and risk management strategies (Chapter 6).

1.1 Flood risk modelling: an overview

The primary method of risk assessment is disaster risk modelling, which estimates the impact of a flood using spatially referenced data (Grossi and Kunreuther, 2005). Input data is based on the risk triangle consisting of: exposure as the value of assets or number of people that can be affected during an event (E); hazard as the probability and magnitude of the event (H); and how susceptible to damage the exposed items are, vulnerability (V) (Kron, 2005). The loss for a given flood (L) is a function of these variables, as shown in eq. (1.1). There are two elements that emerge from these three variables: the human element and the climate element. The vulnerability and exposure components form the human element of the system, since these two elements directly correspond to human behaviour. Exposure changes as the result of socio-economic development in flood-prone areas. Vulnerability can be altered by changing building codes (e.g., Burby, 2001) or retro-fitting buildings (e.g., Poussin et al., 2015) to make buildings more resilient to water damage. The climate element is the hydrological flood caused by local weather and geographical conditions, which provides the hazard input into the system.

$$L = f(H, E, V), f_H' \geq 0, f_E' > 0, f_V' \geq 0 \tag{1.1}$$

There is not only a single possible flood event, and a common way to represent the range of possible floods is through probability-exceedance curves (Grossi and Kunreuther, 2005), as shown in Figure 1.1. A probability-exceedance curve shows that, for example, a flood with an exceedance probability of 0.5 (meaning a larger flood would occur 50% of the time) would have a certain impact.

Risk is thus described as the probability weighted sum of flood impacts (Mechler, 2016), which is the integral of the probability-exceedance curve (Ward et al., 2011). A probability-exceedance curve alters eq. (1.1) such that L is now a function of p, the probability-exceedance, where the smaller the p, the larger the total loss. Risk or the expected loss is shown in eq. (1.2).

$$Risk = \int_0^{PS} L(p)dp \, f_p' \leq 0 \tag{1.2}$$

Equation (1.2) introduces the variable PS, representing flood protection standards. Protection standards are measures such as levees or floodwalls, aimed at preventing floods, which lower the exceedance probability of damaging floods (de Moel and Aerts, 2013). Figure 1.1 shows the effect of implementing two flood risk management measures on the exceedance probability curve: (a) the right panel shows that by implementing flood protection standards, any flood with an exceedance

probability larger than 0.5 is assumed not to occur. (b) Damage mitigation measures are measures lowering flood impacts on e.g. buildings by reducing vulnerability (e.g. elevating a building, or flood proofing the base floor). By implementing such measure (the red line in Figure 1.1), total risk is lowered, reducing the area under the probability-exceedance curve --while maintaining a given level of exposure.
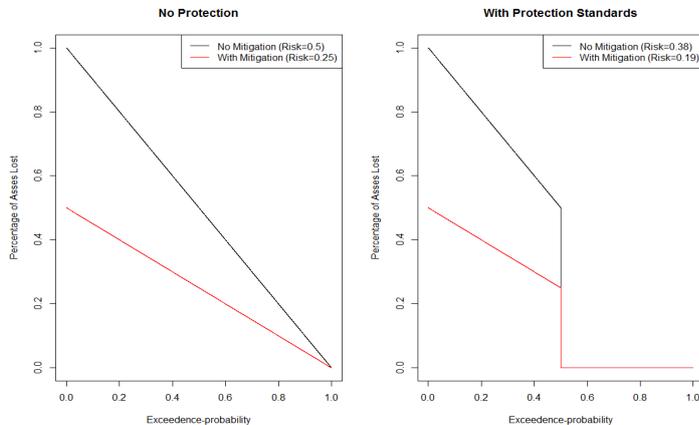

Figure 1.1 An example of a probability-exceedance curve

Notes: The left panel shows risk curves with no protection standards, and only assumes damage mitigation strategies that lower damage by 50%. The panel to the right shows risk curves assuming both protection standards set at a probability-exceedance of 0.5 and damage mitigation strategies that lower damage by 50%.

1.2   Managing natural disaster risk

The increasing trend over time in risk and observed impacts (as noted above) result in a growing interest in flood risk management. There has been a reduction in the overall vulnerability to flooding both globally (e.g., Jongman et al., 2015) and at an individual level (e.g., Bubeck et al., 2012). This is because with growing risk more risk reduction measures become cost-effective (Chapter 5).

1.2.1   Natural disaster risk reduction

Disaster risk reduction (DRR) can be sub-divided into protection and mitigation. Protection reduces the flood hazard (i.e., flood probability) while mitigation lowers vulnerability of people and assets once a flood occurs. Protection measures, such as dikes or similar barriers, can be rather expensive. For example, installing storm surge barriers to protect New York against flooding could cost up to $21 billion (Aerts et al., 2013). The state tends to be the greatest provider of protection infrastructure, because of the public good characteristics of such projects. For example, the Dutch government has invested in dikes that reduce the probability of a flood to 1/10,000 in some areas (Klijn et al., 2004), while the average flood protection infrastructure in Austria is at 1/400 (Scussolini et al., 2016). However, increasing the protection standards to a level that floods never occur is likely to be economically inefficient (Kind, 2014).

Investments in protection infrastructure are not purely beneficial, as such investments can promote 'levee effects'. Levee effects occur because a high degree of protection makes people feel safe, which encourages the growth in exposed assets in protected areas (Tobin, 1995; Vis et al., 2003). This growth in assets implies that the potential flood damage, and hence flood risk, increases. Husby et al. (2014), for instance, show that, after a large-scale protection infrastructure project was conducted in the Netherlands, the affected protected areas tended to experience faster population growth rates. To reduce potential levee effects or manage development more generally, spatial planning can direct development away from flood risk zones to reduce exposure (Kreibich et al., 2014). Moreover, building codes can be altered with the aim of reducing vulnerability to flooding (Burby, 2001).

Mitigation measures can operate at both large and small scales, although they are often employed at a household-level. One method of mitigating disaster risk is through wet or dry flood-proofing

buildings (Aerts et al., 2013). Wet flood-proofing comprises household or business level measures, which aim to limit damage if a flood occurs; for example, by building with water water-resistant materials and having water-resistant floors, and placing electricity and utility installations above flood-water levels. Dry flood-proofing measures aim to prevent flood waters from entering a building, for example by placing flood shields and sealing walls and cellars. Mitigation measures such as the above examples are small-scale measures that can have large benefits in terms of avoided flood damage in the aggregate (Chapter 5).

1.2.2 Natural disaster risk transfer

Risk transfer mechanisms, such as insurance, do not lower the physical impact of a disaster, but spread risks over individuals by providing compensation for damage after a disaster event. In the presence of risk transfer mechanisms, the individual replaces a large randomly occurring loss (flood impacts) with a smaller constant net loss (paying a flood insurance premium). It is commonly assumed that people are risk averse and prefer low volatility in their wealth levels or certainty about their welfare (Mas-Colell, 1995). Risk transfer helps to reduce the financial impact of a disaster on those directly affected by the sharing of flood losses across a wider group (McAneney et al., 2016).

Assuming that the premium is actuarially fair (i.e., the premium is equal to the risk) an individual will buy full insurance (Mas-Colell, 1995) and a constant level of welfare results. A similar finding applies if the premium is not actuarially fair (i.e., higher than the risk), where individuals will not fully insure and still hold some risk themselves (Mas-Colell, 1995). This may be through the use of deductibles or through co-insurance[1], meaning the insured will still suffer some financial impact when flooded. In this case, as long as the 'unfair' premium is not too high, risk transfer mechanisms allow individuals to reduce the volatility in their welfare. In practice, insurance premiums are nearly always larger than the risk faced because of the loading factors insurers charge due to, at least, the administrative costs of providing insurance. The potential increase in an individual's welfare from reducing volatility is not the only benefit of risk transfer mechanisms. Pre-funded compensation mechanisms are the key for recovering quickly after a flood event at a low cost (Botzen, 2013). The smaller fixed premium costs and quick compensation helps policyholders to get back on their feet after a disaster occurs (Botzen, 2013), which limits long-lasting and indirect impacts on the economy (Koks et al., 2016).

Mechanisms for risk transfer can come in many forms, one of which is through the insurance market, which can be led by the private sector, the government, or by both, through a public private partnership. Regardless of the insurance provider, for a policyholder to receive compensation they must have paid the insurance premium. Allowing premiums to reflect the underlying risk a policyholder faces can provide incentives for DRR by acting as a price signal of risk, or by providing discounts for DRR measures taken by the policyholder (Kunreuther, 1996). Insurance companies can have incentives for encouraging their policyholders to actively manage their risk profiles, in order to protect their firm's long-term sustainability. Therefore, a well-designed insurance market or product can combine both primary methods of managing risk (Kunreuther, 1996; Botzen et al., 2009b; Kunreuther and Michel-Kerjan, 2009; Mechler et al., 2014; Penning-Rowsell and Pardoe, 2012; Surminski and Oramas-Dorta, 2014). Creating such an insurance market is challenging. For example, if insurance companies raise premiums to correctly reflect risk, then premiums may become too high, and insurance can become less attractive for especially low-income households in high-risk areas (Botzen et al., 2009a). However, despite the potential conflict with affordability of insurance, risk-based premiums can provide strong incentives for actively managing risk (Chapter 5).

Market, or insurance based, mechanisms are not the only way of sharing losses, since there are also public sector mechanisms such as government compensation after a disaster has occurred. For example, Germany and the Netherlands can use government funds in an ad-hoc manner to provide compensation following a flood. Some governments may be in a good position for loss sharing, due

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[1] A deductible is a fixed value, e.g. the first $100 per claim or the first of claims up to $100 per year. Co-insurance, on the other hand, is a fixed percentage of losses; e.g., the policyholder can only be compensated for 90% of each loss claimed.

to their ability to diversify losses both spatially and intertemporally via taxation and borrowing (Mechler and Hochrainer-Stigler, 2014). This allows for wealth transfers to provide compensation to those affected. Although complete public insurance provision may be less efficient than provision through competitive markets, public insurance provision may more easily meet certain social goals, such as widespread affordable insurance coverage.

A drawback of government compensation is that citizens may become reliant on government compensation, which reduces the incentive for self-preparation. The disincentive for preparedness emanating from government compensation is known as the Samaritan's dilemma or charity hazard (Raschky and Weck-Hannemann, 2007). Ad-hoc state compensation lowers the incentive to buy insurance as, in essence, households gain free insurance coverage. These mechanisms develop out of concern for those affected by natural disasters, which leads to the financing of disaster losses based on principles of national solidarity. The main goals of these public-sector mechanisms, therefore, are equity and access to disaster compensation.

Flood insurance systems must strike a balance between trading off equity concerns with economic efficiency (Chapter 6). Different structures for providing insurance have developed across Europe in response to different risk profiles and different social objectives (Surminski et al., 2016). Across Europe, three stylized market structures can be identified (Chapter 6). The first is solidarity markets, where flood insurance is considered to be a social, rather than a private, good, and the affordability of insurance premiums is important. The affordability of insurance is maintained by mandating insurance purchase across high-risk and low-risk households, combined with support from the government for very high impact events. The second is voluntary markets, whereby households have the free choice of buying flood insurance. The majority of such markets offer limited government support for disaster losses and risk-based premiums. The third is semi-voluntary markets, whereby households, in principle, have the choice of whether to buy flood insurance or not. However, in practise, flood insurance coverage is bundled with more commonly bought insurance products, such as fire insurance, that are often purchased to satisfy mortgage requirements (e.g., Maccaferri et al., 2012). If such insurance is provided in a way that the premium reflects the underlying risk, it may prove to be an effective risk management tool (Chapter 6).

1.2.3 Combing natural disaster risk reduction and risk transfer

Given the expected increase in flood risk across Europe, it is important to combine flood insurance coverage with adequate incentives for promoting DRR by policyholders. Many households in flood-prone areas do not choose to invest in DRR (e.g., Kreibich et al., 2005; Bubeck et al., 2014; Osbergehaus, 2015). The unpreparedness of households could originate from several behavioural heuristics associated with low-probability/high-impact risks (Kunreuther and Michel-Kerjan, 2011). Examples of these heuristics are bounded rationality (Botzen and van den Bergh, 2010) and availability bias (Tversky and Kahneman, 1973). Households act upon their subjectively perceived risk level, which may deviate from objective flood risks. For example, due to availability bias, individuals may underestimate flood risk if a flood has not happened for a long time, which makes it difficult for them to imagine that a future flood would occur. Insurers, on the other hand, have a very strong incentive to gain an as accurate understanding of risk as possible, in order to remain commercially viable. Therefore, insurers have led the way in the use of risk models to understand risk (Grossi and Kunreuther, 2005). As a result, a gap may exist between subjective risk perceptions by households and objective views of risk by insurers. The perception gap can result in problems with using insurance-based incentives in voluntary markets, as households may not buy flood insurance and/or employ DRR measures when they underestimate flood risk. The implications that result from these behavioural heuristics or subjective risk misperceptions highlight the need to study the role that requirements for purchasing flood insurance and insurance incentives for DRR can play in better managing future flood risk.

Nevertheless, household DRR can be a cost-effective adaptation measure (Chapter 2; Chapter 5). Therefore, insurance incentives may be required to promote household DRR, because in the absence

of such incentives relatively few households may employ DRR measures (Chapter 5). A traditional insurance incentive for policyholder-led risk management is a deductible (or co-insurance). Deductibles are not only a response to 'unfair' insurance premiums, but also as a mechanism to prevent moral hazard. Moral hazard occurs when insurance coverage increases the vulnerability to floods because the insured take fewer measures to limit risk. This is because they expect that insurers will compensate their damage irrespective of their risk reduction efforts (Ehrlich and Becker, 1972; Arnott and Stiglitz, 1988). Moral hazard poses problems if the resulting behaviour cannot be observed by the insurer, meaning that increased risk taking is not completely reflected in a higher insurance premium (Chiappori and Salanie, 2000). This is a concern because inadequate premium levels are a common cause of problems for insurance schemes (Surminski and Eldridge, 2015). The presence of a deductible in an insurance policy results in the policyholder having 'skin in the game', which provides the policyholder with an incentive for risk management.

However, not all households may display moral hazard behaviour due to their intrinsic motivations to prepare for flood disasters (Chapter 4) or markets can be structured in a way that reduces the importance of private information (Chapter 6). Regardless, the presence of moral hazard needs to be studied as the European Commission (EC) notes in EC (2013). The Green Paper on Natural and Man-Made Disaster Insurance (EC, 2013) expresses concerns that the presence of moral hazard could result in disaster risks becoming uninsurable. Studying the presence of moral hazard can be problematic in some countries due to the absence of a control group of people without flood insurance. For example, Germany has a voluntary flood insurance market and, therefore, there are households with and without flood insurance, while in France the coverage rate is nearly 100%. Moral hazard should be studied where it is possible to do so, using several data sources and methods embedded in the overall literature to produce results that might be generalizable to a wider population than that studied.

While the deductible may be the most common method of incentivising policyholder risk management, the potential of a well-designed insurance market to stimulate risk reduction goes beyond the deductible. Deductibles may not be sufficient if policyholders underestimate the threat that they face, if they simply not know whether they have a deductible (Chapter 4), or if the deductible is too small. For example, in France the mandatory deductible is €380 per year (Poussin et al., 2013). As an illustration, if there is a 1% flooding probability, as in the department Maine-et-Lorie (Scussolini et al., 2016), then the flood risk has an expected loss for the policyholder of an average of €3.80 per year[2], which is a very small incentive for risk reduction[3]. Insurance premiums can provide stronger incentives for DRR through charging risk-based insurance premiums. Risk-based premiums allow policyholders to be directly rewarded for additional DRR with lower premiums. The external DRR incentive provided by risk-based premiums can build resilience (Kunreuther, 2015) by stimulating policyholders to implement cost-effective DRR measures. In areas where disaster losses are driven by socio-economic development, behavioural incentives offer useful ways of limiting future flood impacts.

To fully embrace the risk reduction potential of insurance, a link between insurance and DRR is required, but this link is currently weak across Europe (Surminski et al., 2015). For example, the study of Thieken et al. (2006) finds that German insurance companies did not provide strong incentives for household-level risk reduction. Moreover, given the increasing pressure that insurers will face without a strong link with DRR, insurance may become unviable in the future (Golnaraghi et al., 2016; Chapter 6). There are several reasons for why the link between insurance and disaster risk reduction has been insufficiently made in practice. The relevant stakeholders tend to view the presence of information asymmetries between insurers and policyholders as a feature that holds back the development of insurance markets (Thistlethwaite, 2016). Information asymmetries limit the

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[2] The expected loss as calculated by €380×0.01.
[3] Even though the deductibles can be increased up to €1,520 in areas that are frequently flooded and do not have adequate community flood risk management plans, the financial incentive in terms of the expected value of flood risk faced by a policyholder remains small (Poussin et al., 2013).

potential connection between insurance and DRR, as premiums cannot be reliably set when the insurer cannot monitor risk reduction activities by policyholders. This issue may be overcome with 'mitigation certificates', in which certified inspectors judge the flood-proofing of a house on which premiums can be set, as is done with the use of elevation certificates in the United States (Kleindorfer and Kunreuther, 2000). For example, since 2013 the German Insurance Association has promoted a flood resilience certificate scheme (GDV, 2016). These certificates are aimed at lowering the transaction costs that prevent insurers and policyholders from acting upon the same information. A remaining challenge with linking insurance to incentives for DRR is that there is little empirical information about how much flood damage can be avoided with specific mitigation measures and how effective risk-based premiums and premium discounts are in stimulating additional DRR by policyholders.

Another obstacle for the adequate functioning of flood insurance markets is that flood insurance premiums can be overly expensive due to insurer aversion to uncertainty of risk and insolvency risks (Kousky and Cooke, 2012, Paudel et al., 2015; Kunreuther and Michel-Kerjan, 2011). Moreover, given the range of risk management objectives that stakeholders have, it can be difficult to find the right balance between risk management incentives and providing affordable insurance coverage (see Chapter 6 for a discussion). While there are frameworks for assessing the risk reduction potential of insurance schemes, an assessment framework for market structures as a whole is lacking. This is because while stakeholders have different objectives, they must achieve acceptable trade-offs between the various outcomes an insurance scheme can be held up against, such as risk reduction, affordability, and high insurance penetration rates. Rather than assessments focusing on a single aspect, a more holistic view is required where outcomes are not evaluated independently, and that is based on the objectives and concerns of the relevant stakeholders.

The desirable structure of the insurance market can be an important object for study. A market's structure can have large impacts on whether insurance meets the risk management objectives placed upon it. A market that charges uniform premiums is unlikely to provide a strong incentive for risk reduction, while a fully private insurance market is likely to charge high premiums to those at greatest risk from flooding. These high premiums in high-risk areas can provide a strong incentive for risk reduction. They limit, however, the overall number of low-income people who can afford to buy insurance or invest in risk reduction, because the upfront costs of actively managing risk can be perceived as placing too large a burden on the policyholder's budgets. A well-designed or structured insurance market can strike a balance between acting as an affordable risk transfer mechanism and a tool for risk reduction. Moreover, such a market can contribute towards integrated flood risk management (Kron, 2005), which places greater weight on the responsibilities of all stakeholders to limit flood risk by acting together in partnerships rather than as individuals. However, while several studies have tried to measure the risk reduction potential of insurance incentives (e.g. Chapter 5) or the potential affordability of premiums (e.g., Kousky and Kunreuther, 2014), we lack an integrated assessment framework for understanding how different methods of providing insurance compare to one another on commonly raised policy objectives.

Finally, when considering the risk management potential of insurance and the risk management incentives an insurance policy can provide, impacts outside of direct tangible (i.e., physical or monetary) losses must be considered. Monetary flood impacts, which are often measured as direct property losses, are an important input for cost-benefit analyses that guide flood risk management strategies (Mechler, 2016). However, a comprehensive societal cost-benefit analysis should also include intangible losses caused by floods (for example, psychological damage and anxiety) (Lamond et al., 2015), to gain a complete view of the effects on welfare. Intangible losses are often neglected in risk assessments, perhaps due to the perceived difficulty of converting intangible losses into monetary values (Prettenthaler et al., 2015), in contrast to the range of methods that have been developed for assessing tangible flood losses (Mochizuki et al., 2014). Moreover, previous studies that have tried to assess the presence of intangible welfare impacts due to insurance or risk

reduction have either focused at a high level of spatial aggregation (Luechinger and Raschky, 2009) or have used choice experiments to elicit hypothetical willingness to pay estimates for avoiding flood impacts (Joseph et al., 2012). A too high level of spatial aggregation can mask the welfare impacts of flood events due to the inclusion of households not exposed to flooding, while the use of choice experiments can expose the results to a range of strategic choices of the participants that are related to hypothetical willingness to pay (Loomis, 2013).

1.3   This thesis's research questions

The main research question of this thesis is: How can insurance and household-level risk reduction measures be combined to create a flood-resilient society? Connecting the two mechanisms can help to meet the Sendai framework's call for increasing investment in disaster risk reduction. Moreover, many insurers and risk managers are starting to believe that without active risk reduction by different stakeholders insurance may be non-viable in the future (Golnaraghi et al., 2016).

To answer this main question this research follows the workflow scheme presented in Figure 1.2 and is based around the following sub-questions:

1. How are flood impacts and household-level flood risk reduction measures valued in terms of welfare? In particular, what are the intangible impacts of flooding and household-level flood risk reduction measures, and how can these be measured and monetised? (Chapter 2)
2. What is the effectiveness of household-level flood risk reduction measures in terms of reducing property damage, and how can this effectiveness be measured while controlling for other factors that influence flood damage? (Chapter 3)
3. Is moral hazard present in natural hazard insurance markets, and is it an impediment to using insurance as an incentive for household-level risk reduction? (Chapter 4)
4. To what degree can direct insurance incentives encourage households to employ flood risk reduction measures? Is there a trade-off between the strength of risk reduction incentives and the affordability of insurance premiums and, if so, how can this be overcome? (Chapter 5)
5. What is the set of insurance market features that best manages trade-offs between economic efficiency and equity concerns of flood insurance market reforms that are needed in Europe to cope with increasing flood risk as a result of climate and socio-economic change? (Chapter 6).

Answering the first sub-question provides insights into the overall welfare benefits of household-level DRR and managing the impacts of flooding more generally. Household-level DRR could form part of wider risk management plans that should be based on a comprehensive cost-benefit analysis (Mechler, 2016), including both tangible and intangible impacts. It is known that floods can severely impact human welfare outside of their direct monetary impacts; causing, for instance, psychological damage or anxiety (Lamond et al., 2015). Showing that flood impacts and flood risk can have large negative impacts on a household's level of welfare strengthens the argument for more actively and proactively lowering risk. Demonstrating that the measures households can take to protect themselves can have positive welfare impacts outside of lower risk levels highlights the need to promote the use of such measures. Nevertheless, the majority of this thesis focuses on tangible monetary flood impacts, which provide more conservative flood risk estimates that are commonly used in practice for advising how society should manage future flood risk.

While Chapter 2 provides a rationale for the role of household-level DRR in overall risk management strategies, Chapter 3 presents a novel method aimed at providing refined estimates of the risk reduction potential of several household-level DRR measures. Chapter 4 complements Chapter 3 by presenting a comprehensive analysis of the relation between insurance coverage and employment of DRR measures to provide an indication of the moral hazard and how expanding insurance coverage may alter policyholder flood preparedness. Chapter 5 uses Chapter 2 and Chapter 3 as a basis to investigate the ability of a compulsory public-private flood insurance market to provide incentives to increase the level of flood preparedness, and the potential trade-off with affordability that may arise

from the use of risk-based premiums. Chapter 6 expands upon the model presented in Chapter 5 to investigate the trade-offs of different flood insurance market structures between several socially relevant indicators across Europe as a whole. In particular, Chapter 6 provides a policy-relevant evaluation of several directions in which flood insurance markets could reform in order to improve the resilience of communities with high flood risk.

Taken together, these five questions answer the overall research question by demonstrating the ability to which insurance schemes with a strong connection to household-level DRR can lower risk in an economically efficient manner, while making an acceptable trade-off with equity concerns.

1.4 The data and methodology employed

The previous sections noted that, when considering the benefits of household DRR, we must consider not only the direct monetary DRR impacts but also welfare more widely. Even though flooding's intangible welfare impacts are often neglected, researchers outside the risk management literature have developed methodologies to investigate welfare directly. These methodologies investigate happiness or subjective well-being (SWB) (MacKerron, 2011), which can be an accurate proxy for welfare (Kahneman and Krueger, 2006; Clark et al., 2008; Krueger and Schkade, 2008). The SWB approach is rare within the risk management literature (Meyer et al., 2013). Exceptions include Carroll et al. (2009) and Luechinger and Raschky (2009), who investigated the consequences of droughts and floods, respectively, on SWB. This approach would, in principle, allow for estimating the effects on welfare of flood experiences, risk perceptions, and household flood preparedness decisions. Chapter 2 adds to this literature by estimating various flood impacts on SWB for a more complete view of welfare impacts by conducting a mediation-style analysis (see Hayes, 2013) of flood risk, overall SWB, and individual SWB domains, such as happiness with an individual's health and living environment. Chapter 2 then presents a novel monetisation of SWB impacts to provide a readily comparable metric for risk management decision processes. This is done using the relation between SWB and income to convert welfare impacts into a monetary value. Moreover, Chapter 2 is the first study to decompose welfare impacts of flooding into tangible (pre-existing monetary values) and intangible impacts (those without pre-existing monetary values), such as discomfort and psychological impacts from flooding.

Accordingly, Chapter 3 presents estimates of the effectiveness of household-level DRR in terms of monetary damage savings. Chapter 3 notes that some studies base the effectiveness of DRR measures on expert judgement and flood risk models (e.g., Holub and Fuchs, 2008; Poussin et al. 2012; de Moel et al., 2013; Dutta et al., 2003; DEFRA, 2008). Moreover, some studies have undertaken empirical research to evaluate the effectiveness of DRR measures (e.g., Kreibich et al., 2005, Bubeck et al., 2012; Poussin et al., 2015). For example, in Kreibich et al. (2005), households were divided into those who had employed a particular DRR measure and those who did not. The average difference in damage suffered was calculated to estimate the measure's effectiveness. The drawback of this approach is that the difference in average damage suffered may not provide accurate estimates of DRR effectiveness, since other factors, like hazard severity, could play a role. Chapter 3 presents the novel use of propensity score matching (PSM) as a method to evaluate the effectiveness of household DRR. PSM refines effectiveness estimates by controlling for variables of influence on flood damage outcomes other than DRR measures, and in particular the variables that overlap between the decision to employ a measure and the process that 'generates' damage. PSM still maintains the basic principle of comparing average difference in damage outcomes between the group that did not employ a DRR measure and the group that did employ a DRR measure.

Chapter 4 studies the relation between disaster preparedness and insurance coverage to assess the presence of moral hazard. Chapter 4 presents four sets of econometric models across German and U.S. natural hazard insurance markets. The first set is a series of probit models linking insurance coverage and risk management strategies; the second set comprises bivariate probit models

investigating if the decisions to buy insurance and employ risk reduction measures are driven by a joint decision process; the third set is the application of PSM to flood damage and insurance coverage in Germany; the fourth set are Heckman sample selection models which examine how the adoption of risk reduction measures is driven by deductibles. Chapter 4 builds on previous studies (e.g., Thieken et al., 2006) by jointly modelling risk preferences, implemented DRR and flood insurance in order to see if behavioural characteristics drive the wish to be insured and employ DRR. Finally, regarding the German sample, Chapter 4 presents the first study to use PSM to estimate how household flood damage is separately influenced by risk and moral hazard. Chapter 4's United States analysis builds on the work of Petrolia et al. (2015) by examining whether their findings hold more broadly to the United States, both geographically and for flood insurance. Chapter 4 also extends Carson et al. (2013) by studying the influence that deductibles have on household DRR by increasing the geographical coverage and by investigating the relationship between the deductible and the actual number DRR strategies employed. Lastly, the U.S. data uniquely utilized real-time survey responses during a hurricane threat to prevent hindsight bias that is present in surveys conducted months or years after disaster events.

Chapter 5 develops an integrated flood insurance and household behaviour model to explore the ability of insurance incentives, such as premium discounts, to promote the implementation of cost-effective household-level DRR measures. The external insurance incentive referred to in Chapter 5 is assumed to be a premium discount that occurs when households employ DRR measures, which implies that insurance premiums are risk-based and respond to such actions. The financial incentives offered by the risk-based pricing of insurance can stimulate policyholder adaptation to flood risk, while potentially conflicting with affordability as premiums may be high in high-risk areas. Chapter 5 also examines the trade-off between risk reduction and affordability. The model in Chapter 5 represents public-private flood insurance in France and Germany. This model provides the initial steps in integrating models of household-level DRR behaviour and insurance premiums under a scenario of changing flood risk over time. The model investigates how, at the NUTS 2 level, household flood risk adaptation behaviour differs under financial incentives as compared to when households act upon one of three scenarios of subjective beliefs of risk perceptions and related benefits of DRR measures. Moreover, Chapter 5 presents the first modelling exercise to estimate the costs of providing flood insurance vouchers that correct for unaffordability. The affordability criterion used takes into account equity concerns across households at risk of flooding and their ability to pay for insurance. Chapter 5 presents a novel contribution to the nascent literature regarding the process of incentivizing the employment of household risk reduction measures (Priest et al., 2016) in order to improve the inadequate linkages between flood damage compensation schemes and DRR across the EU (e.g., Suykens et al., 2016). Moreover, Chapter 5 contributes to this literature by quantifying the potential benefits of strengthening the link between insurance and household-level risk reduction though a simple behavioural model. The results are of a broader interest across the EU, where there is a debate about how to improve incentives for DRR (European Parliament, 2013).

Noting that the link between disaster insurance and financial incentives should be strengthened is part of a wider debate over the most suitable flood insurance market structure in light of increasing risk due to socio-economic and climate changes. Market structures can feature competing levels of public and private sector involvement with differing degrees of risk sharing and risk reduction. In Chapter 6, 26 European insurance markets were evaluated according to various stylized market structures to examine how each market manages the trade-offs between economic efficiency and equity. The stylized markets were identified from current practice and were evaluated against the following criteria commonly discussed in policy debates: insurance penetration rates, the unaffordability of insurance, the degree of incentivised risk reduction, and the degree of risk sharing across high- and low-risk households. Chapter 6 presents a modelling framework for a combined model of flood risk, household insurance purchase, risk reduction behaviour, and insurer behaviour called the dynamic integrated flood insurance (DIFI) model. The DIFI model is based on the modelling framework presented in Chapter 5, but extends the model to account for more risk management

objectives and more complex household and insurer level behaviour across different market structures. The DIFI model estimates the four core policy indicators for two 20-year periods, starting in 2015 and 2035, for areas with a high flood risk. Chapter 6 provides a quantitative study and methodology that offers evidence supporting previous works based on a qualitative analysis of disaster insurance markets.
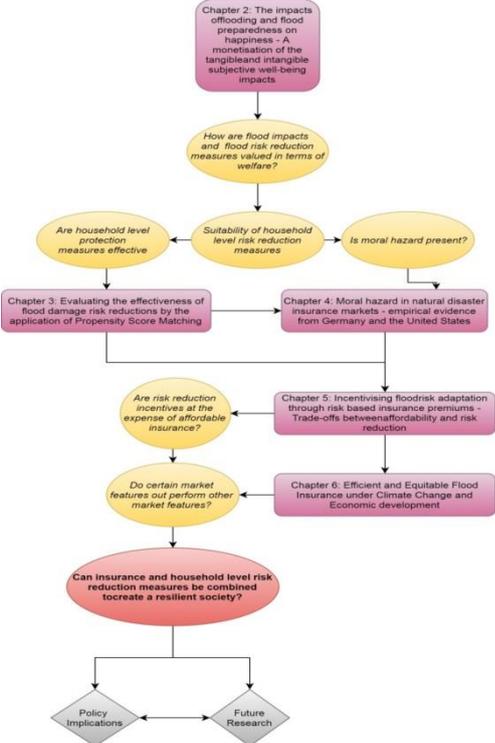

Figure 1.2 Work scheme of this thesis