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## Integrating adaptation behaviour in flood risk analysis

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## Summary

Every year, flood events lead to significant economic and societal impacts. Scientific projections show that the risk of flooding is expected to increase in many regions around the world due to socio-economic growth and climate change. However, current projections of flood risk often assume that adaptation is static, as if the main agents involved in flood management, such as governments, insurers, and households, do not respond to changing flood risk and to each other's adaptation decisions. This assumption limits our understanding of how flood risk will evolve, how adaptation will develop, and how much risk remains after adaptation. To improve our understanding of flood risk in the future, this PhD dissertation explores how the adaptation behaviour of governments, insurers, and households can be included in flood risk analyses and how they shape risk and each other's decisions over time. In this dissertation, flood risk is defined as expected annual damage in monetary terms, which is a function of: the hazard, the land, buildings and assets exposed to flooding, as well as the vulnerability of land, buildings and assets to floods. To investigate how to incorporate decisions into flood risk assessments, the thesis applies different tools such as cost-benefit analyses, behavioural models based on micro-economic theory or psycho-social theory, and agent-based models (ABMs) that integrate the behaviour of agents in a flood risk analysis.

First, this thesis demonstrates how a standard flood risk analysis framework can be combined with a cost-benefit analysis to represent rational decision making by governments, in which investment in flood protection is guided by the economic evaluation of optimal strategies. Chapter 2 provides a first set up of this framework for Tabasco, Mexico, which faces severe floods on an almost yearly basis. The analysis of coastal flood risk shows that without adaptation, the expected annual damage will increase from 0.53 billion USD today to 4.12 billion USD in 2080 as a result of socio-economic development and climate change. For river floods, the cost of damage increases from 1.79 billion USD to 10.6 billion USD in 2080 without adaptation. The cost-benefit analysis shows that, when taking into account climate change, the optimal economic decision would be to raise both river and coastal protection to at least a 100-year protection standard, which would reduce the combined coastal and river flood risk by roughly 10-13 billion USD, depending on the climate change scenario. A sensitivity analysis for a number of assumptions in the risk analysis and cost-benefit analysis is applied, showing the robustness of the optimal investment decisions. The chapter provides a basis for how rational decision making by governments can be

modelled and shows how it can assist the policy-makers in making decisions about flood risk management.

The combined risk analysis and cost-benefit approach is further expanded to all states in Mexico in Chapter 3. The chapter shows how the cost-benefit approach can assist in prioritising where adaptation is needed, and how much funding is required to implement adaptation in each state in Mexico, for both coastal and river floods, and for different climate scenarios. Since consistent, detailed local data is often missing at this scale, the model approach in this Chapter applies global datasets, demonstrating how such large-scale datasets can be used for more detailed local analysis of optimal flood adaptation strategies. The results show that without adaptation, the combined coastal and river flood risk for Mexico can increase from 7 billion USD a year to approximately 126 billion USD a year in 2080 due to socio-economic growth and different climate change scenarios. Optimal protection standards are found to differ per state and climate change scenario, leading to differences in flood reduction outcomes. For river floods, the percentage of risk reduced varies between 15% for Chihuahua under RCP8.5 conditions, to almost 100% for Queretaro under RCP2.6 conditions. For coastal floods, economically optimal protection standards lead to a risk reduction of over 90% for many coastal states under future climate scenarios. The benefits of choosing economically optimal protection standards in Mexico outweigh the significant costs of protection, which were found to range between approximately 75 billion to 120 billion USD over the lifespan of the river and coastal protection, depending on the climate scenario.

While government decision making on flood protection is often supported by tools such as cost-benefit analysis, the adaptation decision by households is commonly more boundedly rational, as it is influenced by subjective risk perceptions, the influence of social networks, the availability of objective information, and flood experience, among other factors. Taking the Netherlands as a case study, Chapter 4 explores how governments can steer household adaptation decisions by providing information on flood risk and how to cope with the risk. The chapter evaluates different communication campaign designs, ranging from large-scale top-down campaigns using mass media, to a more people-centred approach. For this purpose, an agent-based model is designed that captures the heterogeneous preferences and characteristics of households. Additionally, the social network of each household is modelled to explore the extent to which communication propagates through the social network and influences household adaptation decisions. The results of the case study lead to three main findings. First, a tailored, people-centred campaign leads to 2.5 times higher implementation rates of loss-reducing measures than a top-down

mass media campaign. Second, communicating on both coping with floods and flood risk can lead to up to 6.5 times higher implementation rates than communicating on risk alone, which is often the strategy in practice. Third, communication is likely to propagate through social networks, leading to an increase of up to 12% in implementation rates of loss-reducing measures.

Chapter 5 explores the applicability of agent-based models further, including household decision making on the implementation of loss-reducing measures in flood risk analyses for an area in Rotterdam, also in the Netherlands. Here, different behaviour models based on micro-economic theory, representing household decision making under risk, are applied and compared: (a) a model based on expected utility theory, which is the traditional model of decision making under risk; (b) a model based on prospect theory, which represents more boundedly rational behaviour where household overweight low probabilities and under weigh high probabilities; and (c) an amended model based on the prospect theory where flood experience, social networks, and media information also influence decisions. Loss-reducing measures include flood-proofing to protect buildings or purchasing flood insurance. The decision to take such measures is influenced by financial incentives, which are for instance offered by insurance companies. The results show that such an incentive can lead to a reduction of up to 29% in risk for this case study if households act rationally. Moreover, the results of the case study show the importance of including dynamic adaptation behaviour to understand the development of risk, as excluding this behaviour leads to an overestimation of risk in the year 2100 by a factor of two.

Building on Chapter 5, Chapter 6 demonstrates the use of an agent-based model that captures different government, insurance, and household behaviour types for the entire European Union. To overcome the inherent limitations of modelling micro-scale behaviour on a macro scale, this model is developed to run on a high-performance computing (HPC) cluster. The model simulates flood risk over time, comparing the behavioural types of different stakeholder eventuality pairs: (a) boundedly rational and rational households, (b) reactive and proactive governments, and (c) voluntary and mandatory insurance schemes, both with or without a premium discount as a financial incentive to households to reduce risk. The results show that when disaster risk reduction policies are steered from more realistic boundedly rational and reactive behaviour towards more desired rational and proactive behaviour, risk is reduced by 6.7 billion EUR per year in 2050 and by 18.5 billion EUR per year in 2080. When households act rationally, they are responsible for 25% of the total risk reduction. Moreover, the results estimate the residual risk after

adaptation, which needs to be covered by risk-transfer mechanisms such as insurance or the EU Solidarity Fund. Finally, it illustrates how these risk-transfer mechanisms can stimulate disaster risk reduction through financial incentives.

While Chapter 6 shows that proactive governments are an important agent in risk reduction, Chapter 7 shows that this proactive behaviour can lead to adverse effects, as boundedly rational households are less inclined to protect themselves when protection is already provided for by the government. The result is that when a disaster strikes, it has more impact than it would if government protection had not been provided. This process is often named the levee effect or the safe development paradox. The extended model in Chapter 7 includes a stylised location decision by households after a flood strikes or after the government increases protection. Building on the model in Chapter 6, the results in this Chapter show that the aggregated expected damage of floods with a return period of 500 years increases by 28-53 billion EUR when governments act proactively instead of reactively, depending on the climate change and socio-economic growth scenarios. However, results also show that if household behaviour is steered towards rational behaviour, the aggregated expected damage of floods with a return period of 500 years instead decreases by 52-92 billion EUR when governments act proactively instead of reactively. These results highlight the interaction between government and household adaptation decisions, and how adverse effects can be countered by providing financial incentives to stimulate risk reduction. These findings are in line with those found in Chapters 5 and 6.

This dissertation demonstrates how dynamic adaptation behaviour by key agents can be successfully integrated into flood risk analyses using agent-based models. The different Chapters highlight the significant influence that decision making can have on (future-) risk estimates. This information can aid policy-makers in selecting adaptation paths to reduce risk and to improve the contribution of individuals' adaptation. The dissertation concludes with recommendations for further research. First, more empirical data on decision making in face of low-probability/high-impact events is needed to calibrate and validate behavioural models. Second, further research can build on the models developed in this thesis to explore more complex behaviour patterns, such as political change and its consequences for climate and disaster policies, changing housing markets due to changing risk in the area, community actions and efforts, and transformative cultural processes that might influence risk, to name a few. Third, from a more holistic perspective, this dissertation shows the importance of combining social sciences and natural sciences. A similar approach can be applied to other natural hazards such as drought risk assessments and global climate change mitigation efforts.