Risk assessment of natural hazards

Data availability and applicability for loss quantification

Tonje Grahn
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DOCTORAL THESIS

Karlstad University Studies | 2017:16

urn:nbn:se:kau:diva-48324

ISSN 1403-8099


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Distribution:
Karlstad University
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SE-651 88 Karlstad, Sweden
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Print: Universitetstryckeriet, Karlstad 2017
Abstract
Quantitative risk assessments are a fundamental part of economic analysis and natural hazard risk management models. It increases the objectivity and the transparency of risk assessments and guides policymakers in making efficient decisions when spending public resources on risk reduction. Managing hazard risks calls for an understanding of the relationships between hazard exposure and vulnerability of humans and assets.

The purpose of this thesis is to identify and estimate causal relationships between hazards, exposure and vulnerability, and to evaluate the applicability of systematically collected data sets to produce reliable and generalizable quantitative information for decision support.

Several causal relationships have been established. For example, the extent of lake flood damage to residential buildings depends on the duration of floods, distance to waterfront, the age of the house and in some cases the water level. Results also show that homeowners private initiative to reduce risk, prior to or during a flood, reduced their probability of suffering building damage with as much as 40 percent. Further, a causal relationship has been established between the number of people exposed to quick clay landslides and landslide fatalities.

Even though several relationships were identified between flood exposure and vulnerability, the effects can only explain small parts of the total variation in damages, especially at object level. The availability of damage data in Sweden is generally low. The most comprehensive damage data sets in Sweden are held by private insurance companies and are not publicly available. Data scarcity is a barrier to quantitative natural hazard risk assessment in Sweden. More efforts should therefore be made to collect data systematically for modelling and validating standardized approaches to quantitative damage estimation.
List of papers


Author Contributions
The papers included in this thesis are the result of collaborative efforts between main author and co-authors. However, the main author carried out the majority of the work from study initiation, the formulation of research questions, data collection, statistical analysis and the writing of manuscripts. Rolf Nyberg performed the Geographical Information System (GIS) analyses in paper 2 and participated in discussion of the results. In paper 3, Lars Nyberg contributed with advice on manuscript structure and formulations. Henrik Jaldell performed the Monte Carlo simulation in paper 4 while the interpretation of the result was a collaborative effort.
Acknowledgment

I would like to thank everyone who saw my potential and believed in me, especially my supervisors Lars Nyberg, Magnus Johansson and Henrik Jaldell.

I am also grateful to Torbjörn Olsson and Leif Larsson for their inspiring perceptivity and passion, to the Länsförsäkringar Alliance for trusting me with insurance data, and to the Wettergren foundation for getting me started on my Ph.D. program by supporting me financially.

I also wish to thank all my dear colleagues, especially at the Center for Climate and Safety, for not only being great colleagues but also highly valued friends who have supported me all the way.

This is the end of a journey. The purpose of the journey was to turn me into an independent, patient, and well-balanced researcher. I have always been independent so I guess the real challenge was to make me patient and well-balanced.

Even though the Ph.D. program first and foremost is considered to be an academic journey, life inevitably keeps happening, making it a life journey as well. It has been filled with personal challenges and sorrow as well as with adventures and joy. I would not have made it to the end without my fantastic family keeping me grounded and reminding me of the real values in life. A special thanks to my parents-in-law who took care of “all the little ones” whenever it was necessary.

Even though I have come to the end of this journey, it is also the start of a new one. I am filled with excitement, hope and curiosity for what it will bring, and I hope you will all continue to be my companions.

Thank you all!

Tonje
Contents

1. INTRODUCTION .................................................................................. 1

2. OBJECTIVE ...................................................................................... 8

3. METHODS AND MATERIALS .............................................................. 10

3.1 INSURANCE DATA ............................................................................ 10

4. THEORETICAL PERSPECTIVES ON RISK QUANTIFICATION AND ESTIMATION ................................................................. 15

4.1 QUANTITATIVE RISK AND RISK ASSESSMENT .................................. 17

4.2 HAZARD EXPOSURE AND DAMAGE CATEGORIZATION ..................... 17

4.3 ESTIMATING AND VALUING DAMAGE ............................................. 19

4.4 DAMAGE FUNCTIONS - A TOOL FOR VULNERABILITY ESTIMATION .... 20

4.4.1 Residential flood damage functions ........................................... 21

4.5 LANDSLIDE EXPOSURE AND LOSS OF LIFE ................................... 29

4.6 ECONOMIC TOOLS FOR POLICY FORMULATION ............................ 31

4.6.1 Cost-benefit analysis .................................................................. 33

5. RESULTS .......................................................................................... 36

5.1 FLOOD DAMAGE IN SWEDEN 1987-2013 ....................................... 36

5.1.1 Data availability and applicability .............................................. 36

5.1.2 Causal relationships - exposure and vulnerability ..................... 37

5.1.3 Application of results in quantitative assessment ...................... 39

5.2 DAMAGE ASSESSMENT OF LAKE FLOODS ...................................... 41

5.2.1 Data availability and applicability .............................................. 41

5.2.2 Causal relationships - exposure and vulnerability ..................... 42

5.2.3 Application of results in quantitative assessment ...................... 43

5.3 ASSESSMENT OF PLUVIAL FLOOD EXPOSURE AND VULNERABILITY OF RESIDENTIAL AREAS .................................................. 45

5.3.1 Data availability and applicability .............................................. 45

5.3.2 Causal relationships - exposure and vulnerability ..................... 45

5.3.3 Application of results in quantitative assessment ...................... 48

5.4 QUICK CLAY LANDSLIDES AND LOSS OF LIVES ............................ 51

5.4.1 Data availability and applicability .............................................. 51

5.4.2 Causal relationships - exposure and vulnerability ..................... 52

5.4.3 Simulation of fatality curves ...................................................... 52

5.4.4 Application of results in quantitative assessments ...................... 55

6. GENERAL DISCUSSION ................................................................... 56

7. CONCLUSION .................................................................................... 64

REFERENCES ....................................................................................... 66
1. Introduction

Natural hazards pose a threat to humans and our constructed societies. In 2016, more than 411 million people were affected by natural disasters, causing 7,620 deaths and more than US $97 billion in economic damage (CRED 2016). Negative impacts have been increasing during the past century concerning both the number of events and economic damages (Figure 1). Some of the increase can be related to improved reporting and documentation techniques. However, natural hazards and their negative effects are expected to continue increasing, partly as an effect of climate change but also due to development-linked factors such as rapid urbanization, population- and economic growth, and environmental degradation (Guha-Sapir and Vos 2011).

Figure 1. Number of disasters 1950-2015 worldwide, per disaster subgroups geophysical, hydrological and meteorological. Source: EM-DAT (2016).

Natural hazards can be divided into geophysical, hydrological, meteorological, climatological, biological and extraterrestrial events. For an overview see Figure 2. This thesis is based on specific studies of events within the families of geophysical, hydrological, and meteorological hazards.
A potential hazard becomes a risk when vulnerable objects or systems are exposed. Damages caused by hazard exposure can be inflicted directly or indirectly on objects, humans and environments and can be further characterized as tangible or intangible damage. This thesis uses lake floods, rainfall and quick clay landslides to describe possibilities and challenges concerning the quantification of hazard damages.
Because of their different characteristics, they also differ in terms of their threat to human life. Since lake floods are characterized by relatively slow rising water levels, the risks to individuals, objects and systems can potentially be reduced or even avoided, as opposed to the rapid quick clay landslides, which are rarely preceded by warning signs. Intense summer rains are also rapid events but in Sweden they are rarely a threat to human life. In Sweden, flood impacts, whether caused by rising water levels or heavy precipitation, are mainly of a direct or indirect tangible economic character while landslides pose a real threat to human lives in addition to their economic effects. Therefore, this thesis focuses on direct tangible and intangible impacts. Damages are further elaborated on in section 4.2.

While dealing with risk is an ancient practice, the concepts of risk assessment and risk management are relatively new. Jardine et al. (2003) claims it’s been formally acknowledged and practiced using this terminology only for the last 30–40 years. An early milestone in the evolution of risk assessment and risk management was the publication of the guidelines developed by the U.S. Environmental Protection Agency (EPA) in 1976. Then there was a large focus on cancer risk (Jardine et al 2003). Quantitative risk assessment, also called probabilistic risk assessment, was also developed at this time and applied during the 1960 and 1970 in the areas of nuclear power and aerospace (Cooke 2009). Quantitative risk assessment is further elaborated on in sections 4.1.

Concerning natural hazard risk assessment, Gilbert F. White was a pioneer in discussing the area of systematic flood risk assessment and management in his dissertation more than 70 years ago. White understood the need for standardized approaches and frameworks and in addition to being the first to form and discuss the concept “levee effect”, which relates to the increased vulnerability of areas protected to a certain flood level when that flood level is exceeded. He also suggested the application of flood damage functions to estimate extent of flood damage and efficiency of risk reduction (White 1946, White 1964).
There are countless damage functions available through consultant agencies, governmental agencies or in academia for use in the developed world to estimate benefits of flood mitigation in terms of avoided damage costs. Interpretation and application of damage function estimates require insights into the purpose for which they are derived (Meyer et al. 2014). Although residential flood damage functions are internationally accepted, there are relatively few published studies that give detailed information of the methodology of their construction and how they are derived (Smith 1994, Pistrika et al. 2014). Figure 3 presents examples of 8 different flood damage functions. The fundamentals of flood damage functions are further presented in section 4.4.1

![Figure 3. Examples of empirically and synthetically derived relative residential flood damage functions. The figure reflects the large variability in functional form of damage functions. Source: Jongman et al. (2012).](image)

Damage functions are an essential part of economic decision support tools such as cost-benefit analysis (CBA) and cost-effectiveness analysis (CEA). In order to estimate economic efficiency of risk reduction, vulnerability with and without risk reduction needs to be estimated. Damage functions are used to estimate the vulnerability of objects (and humans) when exposed to hazards and are thereby also an essential part of the quantitative risk equation. They have, since they were first introduced, been adapted to other types of natural hazards.
(see e.g. Meyer et al 2013, 2014). Economic decision support tools are further elaborated on in section 4.6.

Flood risk reduction benefits, which are meant to avoid or minimize hazard impacts, often have the same characteristics as public goods. Goods and services with public good properties make it possible for many consumers to benefit from one single unit of provision (Hindriks and Myles 2006). It has been known to promote free-rider behavior, meaning that consumers rely on other consumers to pay for the goods, which is possible because of its characteristics of non-excludability and non-rivalry. Because of these characteristics, the private competitive market will rarely be able to provide sufficient and efficient solutions to disaster reduction.

Due to its public goods properties, the commonly large investment costs, and the transdisciplinary collaboration needed to handle the complexity of natural hazard impacts, risk reduction often needs to be financed by public funding. White (1946) recognized these two aspects of disaster risk reduction early on and acknowledged the need for standardized approaches to flood damage assessment so that different reduction measures could be compared in a rational way, enabling efficient and fair spending of public resources. During the past decades the risk concept has become more complex and the need for standardized methods and frameworks have become even more apparent. Risk and emergency managers in many countries, however, still lack the necessary standardized tools to adequately perform reliable risk assessments (Nastev and Todorov 2013).

Technical progress in combination with development of comprehensive risk assessment methodologies have increased the detail level of scientific knowledge, and well-designed software packages, such as the American disaster assessment tool HAZUS, has increased our capacity to combine and analyse large amounts of data. There are many advantages related to the progress of technical support systems for risk assessment. With such tools we are now able to quickly estimate extent of impact in the aftermath of disasters in order to free sufficient resources for disaster management, and to analyse and support efficient investments in risk reduction of future hazards.
A downside, however, is the decreased transparency of the different components of the risk equation; Probability (P), exposure (E) and vulnerability (V) are handled within the frameworks. Damage functions, which are the key to how risk reduction benefits are estimated, are often buried deep within software tools. It is actually possible for the analyst to be unaware of the basic assumptions of cost and benefit estimation applied in different frameworks. This lack of transparency also raises the question of transferability of frameworks in time and space since damage functions are known to be geographically dependent and sensitive to changes in relative prices of e.g. property (Penning-Rowsell and Chatterton 1977).

Another downside is that comprehensive models for hazard analysis usually are extremely data demanding. Some countries, such as USA and Germany, have been developing their natural hazard databases for decades and other countries, such as the UK, have developed their own standardized approaches for damage estimation. One of the main sources of uncertainty in assessments is the lack of sufficient, detailed, comparable and reliable data (Handmer 2003). Ex-post damage data are used to identify the most important factors influencing damage, to develop models such as damage function and to validate the models (Meyer et al. 2013). Countries that lack the demanded data, or resources to develop their own models or to adopt existing models to the national or regional conditions, are left to crude approaches or to adapting non-adjusted models.

Accurate hazard loss data and sound estimates are needed by policy makers to make sound decisions about disaster assistance, investment in risk reduction, policy evaluation, and scientific research priorities (Downton et al. 2005). Preferably, all types of damage should be quantified and included in the analysis to serve as a basis for decisions on efficient risk management strategies. It is therefore important to identify different types of losses and the factors affecting the losses, and to develop models and tools for measuring the effects (Rose 2009). If only a minor part of the damage is taken into account, the broad perspective is lost and subjective assessments of a more qualitative character will supersede the more objective quantitative
decision basis (Sonnesjö & Mobjörk 2013). Working towards extended quantification will enhance objectivity in risk assessments (Sonnesjö & Mobjörk 2013). The basis of quantification and cost estimation is, however, the data available for quantification.

Known deficiencies related to assessment of natural hazards are, amongst others, lack of data sources, shortcoming of existing methods, distribution of costs within society and use of cost assessments for policy formulation and decision making (Meyer et al. 2013). Estimating cost of hazard exposure is an increasingly important aspect of risk reduction in planning and flood risk management (Tate et al. 2015). Cost information influences the formulation of flood policy including the allocation of funding, regulations and plans aimed at reducing flood risk (Middelmann-Fernandes 2010). State-of-the-art cost assessments are, however, far from delivering comprehensive and precise monetary estimates (Meyer et al. 2013), and expected damage can vary greatly depending on choice of damage function, which can make the difference whether or not a project is economically feasible.

This thesis focuses on the relationships between natural hazards, hazard exposure and damage. The task of identifying and estimating these relationships is important for the development of quantitative models for risk assessment. Further, the thesis evaluates the applicability of empirical damage data as input to quantitative risk assessment and development of damage functions. In order to do so, the role of damages and damage functions in risk assessment and economic analysis must be clarified. This is done in the theory chapter in section 4. The results of the studies included in this thesis are presented in section 5. In section 6 there is a general discussion of the topics of the thesis and finally, section 7 presents the general conclusions of the thesis.
2. Objective

The overall objective of the thesis is to improve the conditions for using decision support tools, such as risk analysis, cost-benefit and cost-effectiveness analysis, to enable efficient risk reduction. In order to apply such tools hazard exposure and hazard vulnerability must initially be identified and quantified. The specific aims of this thesis are:

1) To identify and estimate causal relationships between hazards, exposure and vulnerability by using systematically collected natural hazard damage data.

2) To evaluate the standardized approach of using damage functions for estimating vulnerability.

3) To analyse availability and applicability of systematically collected exposure and damage data for deriving empirical damage functions and as input to quantitative natural hazard assessments in Sweden.

The thesis fulfills the aim through 4 studies and the combined knowledge produced by the research leading to the conclusions of the specific studies. The thesis presents analyses of damaging effects of three types of disasters: lake floods (hydrological), heavy rain (meteorological), and quick clay landslides (geophysical). Two categories of impacts are analysed, namely direct tangible damage to residential property caused by flooding (study 1, 2, and 3), and loss of life caused by quick clay landslides (direct intangible damage) in study 4.

Study 1 contributes to the objective with increased knowledge of flood damage over time, and pinpoints risks that must be further assessed.

Study 2 contributes to the objective by establishing causal relationship between direct tangible damage to residential areas and lake flood exposure. Further, it evaluates the data’s applicability for deriving damage functions and its applicability in quantitative risk assessment.
Study 3 contributes to the objective by establishing causal relationship between direct tangible damage to residential areas and exposure to heavy rain. Further, it evaluates the data’s applicability for deriving damage functions and its applicability in quantitative risk assessment.

Study 4 contributes to the objective by evaluating the applicability of existing quick clay landslide information for identifying relationships between quick clay landslide exposure and direct intangible losses of human life. Further, it evaluates the data’s applicability for deriving damage functions and its applicability in quantitative risk assessment.
3. Methods and materials

Quantitative and qualitative methods have been used in this thesis. While the research questions have guided the choice of methods, the datasets limited and determined the approaches that were possible to apply. Study 1, 2 and 3 analyse insured damages. Because of the large focus on insurance data in the thesis a joint description of this data is provided in this section. The different methods and materials, and the studies to which they were applied, are listed below in Tables 1 and 2. Descriptions of how the methods and material were applied in the studies are placed below the tables.

3.1 Insurance data

Systematically and continuously collected damage data are scarce in Sweden. The most comprehensive damage data sets are held by private insurance companies and are not publicly available. The Swedish insurance group, Länsförsäkringar, has made their damage database available to my research and thereby to flood risk assessments. The regional companies of the Länsförsäkringar alliance together hold the largest market share concerning private home insurance in Sweden, with approximately 30 percent nationwide. There are, however, regional variations in the rates ranging from 23 to 65 percent. The rates have been quite stable over the years.

The Länsförsäkringar database contains information on flood damage from 1987. The information made available to my research concerns insurance claims between the years 1987-2013. The data set contains information about the size of the individual payments paid to insurance holders, the date the damage occurred, or whether payouts were compensation for building damage or damage to inventories. It is also possible to relate payouts to year, month, municipality, and parish. There is no information about the exact location of the damaged property. The payments do not include the deductible, which is set to 10 % of the damage, or a minimum of 10,000 SEK for structural damage and 3,000 SEK for damage to movable property. These deducti-
bles apply to damage caused by flooding.\textsuperscript{1} Other rates apply to other sources of damage.

In Sweden, flood damage to residential property is covered by basic home insurance. The insurance covers damage to buildings and moveable property when the flood is caused by rain of an intensity of 1 mm per min. or 50 mm per day, by snowmelt or by increasing water levels in lakes, rivers and streams. Further, the water must have entered a building by flowing from the surface directly into a building through valves, windows or door openings, or through sanitary pipes.

There are presently no special demands on policyholders related to risk reduction efforts that can affect the terms of insurance payouts other than the general request for carefulness and to follow guidelines concerning water utility systems. No active choice is required to include flood insurance in a person’s home insurance, the price of the policy is not connected to the actual flood risk in a specific area, and no policyholder is refused flood insurance in their home insurance (Länsförsäkringar 2014). To obtain a mortgage on a house, using the property as collateral, the property must be properly insured by an insurance provider accepted by the creditor (Nordea 2014). The insurance coverage amongst homeowners in Sweden can therefore be assumed to be close to 100 percent and the Länsförsäkringar database can be seen as representative of Swedish flood damage to residential property.

\textsuperscript{1} The rates are not fixed and must be checked before applying them to payouts made outside the timeline of this study.
### Table 1. Overview of methods used in the thesis

<table>
<thead>
<tr>
<th>Methods</th>
<th>Study 1</th>
<th>Study 2</th>
<th>Study 3</th>
<th>Study 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Systematic literature review</td>
<td>x</td>
<td></td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Telephone interview study</td>
<td></td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>GIS</td>
<td></td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Regression analysis</td>
<td>x</td>
<td>x</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Monte Carlo simulation</td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
</tbody>
</table>

### Table 2. Overview of materials applied in the thesis

<table>
<thead>
<tr>
<th>Materials</th>
<th>Source</th>
<th>Study 1</th>
<th>Study 2</th>
<th>Study 3</th>
<th>Study 4</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Insurance data (digital and paper archive data)</strong></td>
<td>Länsförsäkringar</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td><strong>Insurance data (insurance database)</strong></td>
<td>Länsförsäkringar</td>
<td></td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td><strong>Interview results (building, flood, house owner characteristics)</strong></td>
<td>Flood victims</td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td><strong>Housing stock information</strong></td>
<td>Statistics Sweden</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Demographics (population, economy, etc.)</strong></td>
<td>Statistics Sweden</td>
<td>x</td>
<td></td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td><strong>Meteorological information (precipitation: gauge data)</strong></td>
<td>SMHI</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Meteorological information (precipitation: radar data)</strong></td>
<td>SMHI</td>
<td></td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td><strong>Meteorological information (wind)</strong></td>
<td>SMHI</td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td><strong>Hydrological information (lake water levels)</strong></td>
<td>SMHI, Arvika municipality</td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td><strong>Skrednet database (landslide information)</strong></td>
<td>SGI</td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td><strong>The Swedish natural hazard database</strong></td>
<td>SGI</td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td><strong>Land elevation information</strong></td>
<td>Lantmäteriet Arvika municipality</td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
</tbody>
</table>

Time series cross-sectional analyses using the fixed effect model (FEM) were applied to a data set. The cross-sections were the Swedish counties (län). Combining time series data with cross sectional data increases the number of observations available for analysis compared to solely applying time series analysis to aggregated data at national level. The method produces more informative data, less collinearity among the variables, more degrees of freedom and more efficiency (Baltagi 2013). The FEM-regression model was used to remove the effects of county individual time-invariant characteristics by subtracting county means of variables from every observation and then using only the deviation from the mean to estimate effects of changes in time-variant factors upon the dependent variable (Cameron and Trivedi 2010). The estimated effects therefore relate to the general variation in the number of insurance payouts over time at national level in Sweden.


The study was performed using the flooding of Lake Glafsfjorden and Lake Vänern in 2000/2001 as case studies. Damage data and individual building and home owner characteristics were extracted from insurance databases and from paper archives at the insurance company, Länsförsäkringar Värmland. A semi-structured telephone interview study and subsequent content analysis with afflicted policy holders and in-depth interviews with several home owners was also carried out. Information on lake levels, wind condition, elevation and the geographical location of buildings and damage was compiled in a Geographical information system (GIS). Regression analysis was applied to analyse the relationship between building damage and flood characteristics, geographical factors, building characteristics and house owner characteristics.

Study 3: Assessment of pluvial flood exposure and vulnerability of residential areas.

The size of insurance payouts was extracted from the Länsförsäkringar database. Regression analyses were used to analyse the relation-
ship between pluvial flood damage and potential explanatory variables. The sizes of insurance payouts at object level and aggregated at municipality level were used as dependent variables. Population density and meteorological characteristics were tested as explanatory variables. Meteorological data were provided as radar data by the Swedish meteorological and hydrological institute. In addition to daily amount of precipitation, the radar data contained both temporal and spatial information that could be tested as explanatory variables for damage extent.

**Study 4: Assessment of data availability for the development of landslide fatality curves.**

This study analysed fatalities caused by quick clay landslides using information from the databases Skrednet and Natural hazard database. Regression analysis was used to explore the relationship between fatalities and number of exposed humans, country of occurrence and year of occurrence, based on the hypothesis that these variables affect the number of fatalities per landslide.

Monte Carlo simulation was performed to take the uncertainty in the relative frequency of landslide fatality rates as a function of the number of exposed humans per landslide into account. The Monte Carlo simulation was performed by simulating 1,000 trials from each landslide. The simulated data set, thus included 40,000 simulated observations.
4. Theoretical perspectives on risk quantification and estimation

In this thesis I argue that there is a strong relationship and dependency between identification of causal relationships between exposure and object vulnerability, damage estimation and the reliability of risk assessment and economic analysis for risk reduction purposes. I have visualized this relationship in Figure 4. This dependency is the context and the very motivation for the studies included in the thesis. Causal relationships between exposure and vulnerability are a prerequisite for deriving damage functions. The damage function is an essential component of the quantitative risk equation. The risk equation serves as input to quantitative risk assessment. The CBA framework and the risk management processes, such as the ISO standard risk management framework (ISO 2009), overlap since they both have the risk assessment as the central part in their frameworks and are not necessarily two separate processes.

This section of the thesis focuses on the theoretical aspects of assessing hazard consequences and its relation to risk management and economic analysis for policy purposes.
Figure 4. The relationship between the risk equation (P, E, V), cost-Benefit analysis (CBA), and the risk management process.
4.1 Quantitative risk and risk assessment

Quantitative risk (R), also called probabilistic risk, is usually described as a function of the probability of a hazard (P), the exposure (E) caused by a hazard, and the vulnerability of exposed assets (V). The majority of flood risk analyses take a technical approach, focusing on the first part of the function (P). Potential consequences (E*V) have not attracted the same scientific interest despite their obvious impact on the outcome of risk estimations (R). Damage modeling has not received much scientific attention and the theoretical foundation of damage models could be further improved (Kelman & Spence 2004, Wind et al. 1999). The impact of natural hazards on society depends on multiple factors including type of hazard, location, duration and the size and the vulnerability of the exposed population (CRED 2015). Seifert et al. (2010) emphasize that due to differences in characteristics, damage assessment needs to be done separately for each kind of disaster.

4.2 Hazard exposure and damage categorization

There are several, quite similar, ways of categorizing damages. The most common categorization was first suggested by Parker et al. (1987), who divide impacts into direct and indirect impacts on object and systems, and further, into tangible and intangible impacts (Table 3).

<table>
<thead>
<tr>
<th></th>
<th>Tangible</th>
<th>Intangible</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Direct</strong></td>
<td>Physical damage to assets:</td>
<td>Loss of life</td>
</tr>
<tr>
<td></td>
<td>Buildings</td>
<td>Health effects</td>
</tr>
<tr>
<td></td>
<td>Contents</td>
<td>Loss of ecological goods</td>
</tr>
<tr>
<td></td>
<td>Infrastructure</td>
<td></td>
</tr>
<tr>
<td><strong>Indirect</strong></td>
<td>Loss of industrial production</td>
<td>Inconvenience of post-flood recovery</td>
</tr>
<tr>
<td></td>
<td>Traffic disruption</td>
<td>Increased vulnerability of survivors</td>
</tr>
<tr>
<td></td>
<td>Emergency costs</td>
<td></td>
</tr>
</tbody>
</table>

A very similar categorization approach is presented in Meyer et al. (2013), dividing flood damage into cost-categories. It is based on Parker et al. (1987), but classifies business interruption cost as a separate
sub-category since these costs are expected to require different cost assessment methods than other indirect damages. It further includes risk mitigation costs in the framework. The categorization approach in Meyer et al. (2013) therefore results in five cost categories: direct costs, business interruption costs, indirect costs, intangible costs and risk mitigation costs.

Direct tangible impacts can be considered to be the most “visible” economic consequence (Sterlacchini et al. 2007). It is caused by physical impact with property or other objects, which leads to destruction of elements or reduction of their functionality (Vranken et al. 2013). The most frequently used approach to estimate direct tangible damage costs is the use of damage functions (Meyer et al. 2013), which are further elaborated on in section 5.1.

Indirect damage occurs beyond the actual event and affects a wider area in space and time than that directly involved in a hazard zone (Kreibich & Thieken 2008, Sterlacchini et al. 2007). It is caused by disruption in economic and social activity caused by direct losses or business interruption (Pfurtscheller 2014, Vranken et al. 2013, Rose 2009, Sterlacchini et al. 2007). Indirect effects can also be referred to as ripple, multiplier, general equilibrium, macroeconomic or societal effects, and can include off-site business interruption, reduction in property values, stock market effects, increased unemployment, sociological effects and environmental effects (Rose 2009).

Intangible damage can be caused both by direct and indirect effects of hazards. Indirect intangible damage includes trauma and loss of trust in authorities (Merz et al. 2010). Direct intangible damage includes loss of life, injuries, loss of memorabilia, psychological distress, damage to cultural heritage and ecosystems (Merz et al. 2010). Intangible effects are frequently mentioned in publications assessing the consequences of natural hazards. Their importance in mitigation decisions are recognized but seldom actually estimated (Conhaz 2012, Messner et al. 2007, Tunstall et al. 2006). As it takes some effort to express these damages in monetary terms, they are often not included in cost assessments of natural hazards resulting in incomplete and biased assessments (Conhaz 2012).
Only direct tangible and intangible impacts are further addressed in this thesis.

4.3 Estimating and valuing damage

Cost is a widely accepted unit for expressing extent of impacts and vulnerability to hazards (Sterlacchini et al. 2007). According to Meyer et al. (2013), different estimation methods are needed for different damage categories, which imply that cost estimation of different types of damage needs to be performed separately and then merged when included in an economic analysis or risk assessment.

Studies 2 and 3 in this thesis address direct tangible flood damages to residential buildings. The insurance compensations used to identify risk factors and to estimate damage costs represent restoration costs and replacement costs. Restoration cost and replacement cost based on market values for goods and services are the common input to the estimation of direct tangible damages (Messner et al. 2007, Meyer et al. 2013). When objects can be assumed to be completely destroyed, the estimation process is more straightforward than when only parts of the asset value are lost. In the latter case the different objects’ (assets) vulnerability to different hazards and hazard intensities need to be estimated, which can be done by using damage functions if they exist for the specific hazard, assets and location. See section 4.4.

Study 4 in this thesis explores available data in order to quantify lives lost due to quick clay landslides with the aim to facilitate the inclusion of these intangible consequences in future landslide risk assessments and the economic analysis of risk reducing measures. Since intangible damages don’t have market values alternative valuation methods can be applied. Approaches for translating non-market values into monetary units are divided into revealed and stated preference methods. Revealed preference methods observe actual market behavior, while stated preference methods elicit individuals’ willingness to pay in hypothetical markets (Meyer et al. 2013, Whitehead & Rose 2009, Messner et al. 2007).
If measured in monetary terms, direct intangible effects on human life can make up a large part of the benefit estimation in a cost-benefit analysis (CBA) of risk reduction since benefit estimation in a CBA of risk reduction projects is equivalent to damages avoided (Ganderton 2005). Intangible effects do not necessarily have to be expressed in monetary units to be included in decision support frameworks, e.g. in cost-effectiveness analysis (CEA). They can be included as non-monetary units (Meyer et al. 2013). See section 4.6. In order to be included in economic analysis or quantitative risk assessment, however, both tangible and intangible impacts must be identified and quantified.

4.4 Damage functions - a tool for vulnerability estimation

Jongman et al. (2012) found that cost estimations are sensitive to uncertainties in both exposure and vulnerability of objects to hazards, but that uncertainties in vulnerability have larger effects on cost estimates than uncertainties in hazard exposure.

The concept damage function has already been mentioned several times so far in this thesis and can be seen as an umbrella term for functions expressing vulnerability of exposed humans and objects. What they estimate, their level of detail and how they are derived depends on the purpose of their application. This section will in general terms explain the concept from a natural hazard context. My main focus on damage functions is related to flood damage estimation for residential property and a more detailed elaboration on residential flood damage function is presented in section 4.4.1. While the focus in the section is on residential areas, the scientific reasoning also applies to other vulnerabilities.

Damage functions can be applied both in ex-post and ex-ante analysis (Tate et al. 2015). In ex-post analysis, they can be a tool to quickly allocate resources for assistance in the recovery and rebuilding phases after disasters (Meyer et al. 2014, Tate et al. 2015). They can cover different spatial scales, from the micro to the supra-national level. At the supra-national level, they can be used to identify and compare risks related to cross-border risks such as flood risk in cross-border river
basins, and thereby serve as input to compensation allocation by solidarity funds such as the EU solidarity fund (Jongman et al. 2012). Global, pan-European, and supra-national damage functions can also be used to measure effects of different time variant risk factors upon flood damage, such as climate change and socio-economic growth (Mechler & Bouwer 2015, Barredo 2009). These effects can then be used to communicate changes in risk over time to stakeholders. Most often, however, flood damage functions are used in ex-ante analysis, e.g. cost-benefit analysis, or hazard assessment tools e.g. HAZUS, to estimate and compare the benefits of different risk reduction projects and to evaluate the economic feasibility of implementing actions to decrease flood damage (Meyer et al. 2014, Tate et al. 2015).

4.4.1 Residential flood damage functions

Damage functions have a long tradition in flood damage assessment where they are also referred to as stage damage functions, depth damage functions, vulnerability functions, or susceptibility functions (Meyer et al. 2013, Jongman et al. 2012, Elmer et al. 2010, Kreibich & Thieken 2008, Messner et al. 2007, Thieken et al. 2006, Kates 1965). Flood damage assessments often focus on private housing (Meyer et al. 2013) and when damage functions are used as input to a cost-benefit analysis, residential areas and damage to buildings become very influential on the outcome of the analysis. Reliable residential flood damage functions are therefore essential for flood loss estimation (Elmer et al. 2010a, Gerl et al. 2014, Tate et al. 2015, Yang et al. 2015), and hence also to quantitative flood risk assessment and policy formulation. It has been shown that the residential flood damage functions are the most important component in an economic analysis of flood risk reduction (Davis et al. 1992).

There are a few basic assumptions that apply to residential flood damage functions independent of how or when they are derived:

1. Depth-damage relationships are based on the assumption that water height and its relation to structure height is the most important variable in determining expected value of damage to buildings (Davis et al. 1992, Penning-Rowsell and Chatterton 1977).
2. Similar structures/properties, when exposed to the same flood characteristics and water depths, can be assumed to experience damages of similar magnitude or proportion to actual values (Davis et al. 1992, Penning-Rowsell and Chatterton 1977).

3. Asset values are to be represented by depreciated values of the structures and content (Messner et al. 2007, Dais et al. 1992, Penning-Rowsell and Chatterton 1977).

How asset values are actually assigned differs somewhat between studies. In Bubeck et al. (2011), some of the models apply depreciated asset values while other models apply replacement cost. When deriving the Flemish functions (Belgium) for residential damage, market values were used (de Moel and Aerts 2011). Often the assignment of asset values is not specified.

**Absolute and relative damage functions**

Flood damage functions can express damage in monetary absolute units, or in relative terms as an index or percentage of total value (Messner et al. 2007, Meyer et al. 2013). The absolute functions and the relative functions therefore differ in the way they integrate monetary values into the damage calculation. The absolute damage function expresses damage in absolute values relating each water depth to an absolute monetary value. Absolute functions are considered by Davis et al. (1992) to be useful only when applied to particular buildings at one point in time.

The relative damage functions express vulnerability as a percentage of asset values, such as structure damage as a percentage of structure value, and contents as a percentage of contents value, for each level of water. The approach requires the total value of the assets at risk within an area to be assessed.

The standard depth-damage relationship applied to residential property often incorporates a building to content relationship (Davis et al. 1992), meaning that content damage often is estimated as a percentage of building value. For residential property, US Army Corps of Engineers applies a ratio of 25-50 percent of building value (Davis et al.
The principal assumption is that content value increases with household income, except for very poor households.

**Empirically and synthetically derived damage functions**

Damage functions can be derived using empirical or synthetic approaches. Empirical damage functions are based on observed flood damage data or post-flood survey data on affected properties, the type of each property, flood characteristics and extent of damage, gathered after flood events (Messner et al. 2007). Post-flood survey is, however, time-consuming and expensive and depends on the actual occurrence of floods. The damage functions are usually derived from the empirical data using regression analysis. This is seen as the best method of measuring the effect of individual damage influencing variables. It can also measure the strength of the relationship between damage and several variables, and the explanatory power of the model itself (Messner et al. 2007, Davis et al. 1992). The regression approach, however, requires a large sample size as the whole variety of different types of building structures and building material must be represented (Messner et al. 2007). The approach was for long, uncontradicted, seen as the most correct approach to derive damage functions. However, due to often low explanatory capacity of the derived regression models their capacity for predictive purposes have been challenged Smith 1994, Penning-Rowsell and Chatterton 1979, Grigg and Helweg 1975, Davis et al. 1992).

Figure 5 presents an example of an empirically derived residential flood damage function. The empirical regression approach is the method used in the different studies of this thesis to identify and quantify causal relationship between exposure and damage. An alternative to the empirical damage function would be the synthetically derived damage function.
In contrast to empirical damage functions, synthetic functions can be constructed based on hypothetical levels of flooding. Typical housing structures and quantity of contents are used to analyse what would be the damage at different flood levels. The value of the components is assessed and susceptibility of each of these items is estimated by expert judgments (Messner et al. 2007). The major advantage of the synthetic approach is that it does not require the occurrence of a flood. The method is, according to Davis et al. (1992), said to generally be quicker and less expensive than post-flood surveys. A disadvantage is the hypothetical nature of the functions. The approach requires expert analysts, and an understanding of specific flood circumstances and how it will affect buildings. Since the synthetic damage functions are derived independently of the flood experience, they provide a set of internally consistent estimates under conservative economic assumptions (Davis et al. 1992). Despite the methodological differences between empirical and synthetic approaches, the approaches can also be mixed, for example, the default depth-damage curve in the HAZUS flood model was developed based on expert opinion, historical damage data, and numerical modeling (FEMA 2016, Nastev and Todorov 2013).
Factors effecting flood risk

Different types of floods, such as riverine floods, flash floods, storm surges, slowly rising lake floods or inundation due to levee breaches or groundwater rise, probably cause different kinds and extent of flood damages. Therefore, analyzing how and to what extent different flood characteristics impact on buildings is highly relevant.

Flood damage caused by riverine, lakes and coastal flooding are said to be influenced by: depth (in-stream water levels or land-based inundation depth), volume, flow velocity, duration of flood, time of occurrence, water quality, sediment or debris load, contamination (chemicals), building construction, age and materials, precaution, early warning, lead time and information content of flood warning, previous experience with flooding, and quality of public response in a flood situation (Boettle et al., 201, Green et al. 2006, Komolafe et al. 2015, Messner et al. 2007, Merz et al. 2004, Middelmann-Fernandes 2010, Thieken et al. 2004, Yang et al. 2015).


A challenge in damage loss modeling is to identify how and to what degree different factors influence the damages (Elmer et al. 2010). Above listed factors for different types of floods are to some extent
overlapping and are all potential predictors of flood vulnerability that might be used for deriving flood damage functions.

Water depths alone poorly explain the variability in damage to buildings (Merz et al. 2004), since flood damages are determined by various factors besides water depth. Thieken et al. (2007) found that, in addition to depth, flow velocity is important to consider in areas prone to flash floods. Further, in regions affected by levee breaches the damage influencing variables contamination and duration had significant effects, despite moderate water levels. Thieken et al. (2005) found that water level, flood duration, and contamination of the water are the most influential factors for building and content damage, but also that building characteristics, in this case building size, and the building value are of importance for the extent of flood damage. Furthermore, the study also showed that private precautionary measures can reduce flood losses, but official flood warning and emergency measures have less influence. Socioeconomic variables and flow velocity were found to have only small effects upon the extent of flood damage (Thieken et al. 2005). Further, also recurrence interval has been found to affect the extent of residential damage (Elmer et al. 2010).

Despite the agreement on the multifactorial aspect of flood damage, the literature in this area is scarce, not very nuanced, and the impacts of the different damage influencing variables upon the extent of damage are not well understood. A few studies have made the effort to derive functions that account for more, or other factors, than water depth.

Penning-Rowsell et al. (2013) take flood warning into account but express this variable with a curve representing lower vulnerability when warning time is given. Dale et al. (2004) have developed velocity-stage-damage functions for Australian residential buildings (Middelmann-Fernandes 2010). The functions do not account for water depth so the model is still a single-parameter model. In addition, the functions only represent the buildings that, because of flooding, get destroyed when sliding off their foundation, and need to be combined
with other functions (for example depth-damage-functions) to include other residential flood damages.

Some multifactorial functions exist in the literature that account for more than one damage influencing variable, e.g. FLEMOps\(^2\) considers water level, building, type and building quality, and FLEMOps+ includes private precautionary measures and water contamination (Thieken et al. 2008). Elmer et al. (2010) have further developed these models to include recurrence intervals, FLEMOps+r. The functions used in the FLEMOps-family are step-functions applying threshold values. Except from Yang et al. (2015) that could not find any clear advantage of using multifactorial residential flood damage functions for river basin planning in Bangladesh, peer reviewed literature shows that simultaneous accounting for several damage influencing variables improves the reliability of flood damage modeling (Elmer et al. 2010b, Gerl et al. 2014, Schroter et al. 2014, Thieken et al. 2008). The FLEMOps+r performs particularly well (Elmer et al. 2010b).

The down-side of multifactorial models is that they are extremely data demanding (Gerl et al. 2014). The large sets of studies emphasizing the variety of circumstances that impact on the extent of flood damage, together with the low predictability of the variable flood depth alone, indicate that more research should focus on including more damage influencing variables into damage estimation. The greatest uncertainties in estimated damages concern small water depths and smaller flood events. The uncertainties can lead to significant over- and under-investments in flood mitigation (Wagenaar et al. 2016).

The following indicators of risk were identified through a scientific literature review: damage cost or number of damages (Zhou et al. 2012, Highfield et al. 2013, Kang et al. 2005), water depth inside buildings (Meyer et al. 2013, Messner et al. 2007), volume and intensity of rain (Pitt 2008, Zevenberg et al. 2010), spatial distribution of rain (Pitt 2008, Leitao et al. 2013), sewer system capacity and sewer

\(^2\) Flood loss estimation model for the private sector (FLEMOps)

Validity and transferability of residential flood damage functions

The damage functions are commonly applied, even to different regions without further validation, mainly due to the lack of damage data (Cammerer et al 2013, Merz et al. 2010). Cammerer et al. (2013) have, however, found that functions adapted from homogeneous regions and floods estimated observed damage well, while damage functions derived for areas that differ concerning e.g. socioeconomic level, building structures or for different types of floods clearly overestimated flood damages in the case study area. Pistrika et al. (2014) applied data that were deemed highly compatible both spatially and damage wise, and found that the damage estimates differed by 10 percent. Pistrika et al. (2014) concluded that with lower compatibility, there will be larger difficulties in obtaining acceptable functions.

To decrease uncertainty, loss models should be derived from related regions with similar flood and building characteristics, and more comprehensive loss data for model development and validation are needed (Cammerer et al. 2013).

Validity and transferability of models spatially or in time is a major gap in flood damage modeling (Hasandzadeh Nafari et al. 2016, Albano et al. 2015, Thieken et al. 2008), and Meyer et al. (2013) questioned the extent to which transferring damage functions is at all possible.
**Distributional aspects of flood damage functions**

Flood damage functions only estimate the asset values at risk in case of flooding. Lower quality buildings and areas mostly occupied by lower social classes are therefore valued less than higher social classes (FEMA 2014, Penning-Rowsell and Chatterton 1977, Penning-Rowsell et al. 2013). This is also the case when estimating the value of house contents. Lower social classes are assumed to have lower value possessions. Residents belonging to higher social classes are believed to be better equipped to handle the shock a flood event may impose on the private economy and to have shorter recovery time (Penning-Rowsell and Pardoe 2012). It is essential to consider which areas benefit most from a measure and which areas do not (Albano et al. 2015).

**4.5 Landslide exposure and loss of life**

Damage caused by landslides mostly affects private homes, road networks, and other infrastructure (Guzzetti et al. 2006). Humans are, however, an essential part of the damage potential because landslides are associated with high rates of traumatic injury and mortality caused by trauma and suffocation (Keiler et al. 2005; Keim 2008). The threat that landslides pose to human life is often the main concern of landslide risk reduction. Human beings are most often exposed where they live (Jaedicke et al. 2009) or work, or when in transition (Agrawal et al. 2013). Research quantifying risks to human lives when exposed to landslides does exist, but is not extensive. A considerable part of the research conducted into landslide mortality has been using Italian landslide records.

Risk factors affecting the extent of impact to human life and health when exposed to landslides are the number of exposed individuals, sex, age, type of injury, severity of injury, type of medical assistance, and where the injury occurred (e.g. at home, inside, outside, or in a vehicle) (Agrawal et al. 2013).

Zhang and Zhang (2014) examined factors involved in human flight behavior related to rapid landslides along roads in China. They showed that the human vulnerability when exposed inside buildings depends on the characteristics of the landslide and the technical re-
sistance of the buildings, but also that individual behavior and personal attributes (i.e. age, sex, disability, running speed, response, education, and prior experience with landslides) are of great importance for successfully escaping a landslide. People with reduced health statuses are also more vulnerable when exposed to disasters (Keim 2008). The importance of personal attribute factors to human vulnerability is confirmed by Viscusi (2006), who claims that the magnitude of loss of human life depends on factors such as individuals’ exposure to hazards and their levels of self-protective behavior. Lacasse et al. (2010) further pointed out that the day of week, time of day, and functioning warning systems are risk factors that should be taken into account. Furthermore, healthy people are less likely to suffer disaster-related mortality and are therefore more disaster resilient (Keim 2008).

General methods for estimating consequences such as loss of life have not been standardized to the same extent as estimations of hazard probabilities (Jonkman et al. 2010). Jonkman et al. (2010) presented a general approach to estimating loss of life for “low probability-large consequence” accidents and disasters. This general approach includes an assessment of physical effects associated with an event, determination of the number of exposed persons, and determination of the mortality amongst the exposed population.

Previous articles reviewed for this thesis have quantified fatalities as frequency rates: the average number of fatalities per event, per year, per month, per day, per area of occurrence or expressed as the number of deaths per 100,000 inhabitants for a given population over a predefined time period (Cascini et al. 2008, Giannecchini and D’Amato Avanzi 2012, Guzzetti et al. 2005, Hilker et al. 2009, Pereira et al. 2014, Salvati et al. 2010). Methodologically these studies differ concerning the observation inclusion criteria that are used when deriving a fatality (or mortality) rate. Guzzetti et al. (2005) combined the number of missing people with the number of deaths when estimating fatalities. Salvati et al. (2010) also included injured humans as well as those killed and declared missing. Giannecchini and D’Amato Avanzi (2012) did not distinguish between flood and landslide fatalities. The studies also differ in length of time periods used for estimat-
ing a landslide fatality rate. Guzetti et al. (2005b) included information from landslides going back to 1279, and Salvati et al. (2010) as far back as year 68. How well the oldest landslides reflect present human vulnerability to landslides is not clear.

Salvati et al. (2010) also performed a more detailed risk evaluation for Italy for the time period 1950-2008. They compared magnitude of events between regions and time periods by modeling distributions of flood and landslide events with causalities taking into account the frequency and intensity of events. They performed the analysis using a Zipf distribution which is a discrete distribution often used for modeling rare events for a finite population size. The analysis performed by Salvati et al. (2010) requires an abundant amount of data. This is available in Italy since Italy has access to more data, as the country has suffered substantial losses to landslides, has a strong tradition of historical research, and that an extensive part of the landslide damage literature stems from Italian research groups.

To increase the knowledge of the risk of landslides in Sweden, the Swedish Geotechnical Institute (SGI), at the Swedish government’s initiative, performed comprehensive risk analyses of landslide risks in the Göta River valley. The main focus was on the hazard event (i.e. stability analysis), but a proportion of the analyses was also dedicated to identifying, quantifying, and, as far as possible, monetizing potential future damage from landslides (Göransson et al. 2014, SGI 2012). SGI developed a method for quantifying risk of losing lives and added this type of consequence to other types of consequences (i.e. buildings, infrastructure, and industrial damage, etc.). A prerequisite for applying the method is a quantification of human vulnerability when exposed to landslides. Vulnerability was calculated as the relative frequency of fatalities and exposed population (evacuated population not included) using historical records (SGI 2011).

**4.6 Economic tools for policy formulation**

The benefits of natural hazard mitigation are the losses that can be avoided by mitigation actions (Rose 2009). Costs arise when implementing, engineering and maintaining interventions, and from the
negative effects of such interventions on our society and natural environment. Several methods exist for integrating economic aspects of natural hazards with risk analysis and the risk management process to optimize the mitigation process. It supports decisions on the actions that are most effective to society, or most likely to reach a predefined target. Commonly applied approaches are mentioned briefly below, but the main focus of this section lies on the cost-benefit analysis, its role as a decision-making support tool and its relation to risk analysis.

*Loss estimation modeling* has since the 1990s been widely used because of the emergence of geographic information system technology (GIS), which makes it possible to overlay hazard data onto maps (Rose et al. 2007, Meyer 2007, Messner et al. 2007). Loss estimation of natural hazards combined with hazard data and exposure data, thus providing information for benefit estimation, makes up an essential part of an economic analysis.

In *cost-effectiveness analysis* (CEA) the benefits of a project is not measured in monetary units. The method allows for intangible damages to be included as a non-monetary target measures (Meyer et al. 2013). CEA can be used to compare mitigation actions when a target is predefined and decision support is needed to choose the approach that most effectively fulfills that target. Only a few examples of the application on cost-effectiveness analysis of natural hazard mitigation have been found in the peer reviewed literature. Fuchs et al. (2007) demonstrate the application of cost-effectiveness analysis of avalanche risk reduction mitigation in Davos, Switzerland and concludes that CEA gives good approximations to cost efficiency of risk reduction strategies but that there are many uncertainties.

Economic analysis of flood hazard risk reduction is complex but an essential tool to guide policy makers, providing important rationale information in the decision making process, and enabling more efficient allocation of public resources (Godschalk et al. 2009, Boardman et al. 2014, Jonkman et al. 2004).
4.6.1 Cost-benefit analysis

The primary value of the CBA lies in the information it can provide to decision makers and, according to Ganderton (2005), it must be seen as an input to a larger decision-making process rather than an end in itself. According to Kågebro and Vedin-Johansson (2008), the main advantage of CBA is its systematic approach to identification and evaluation of effects that can lead up to more well-founded decisions and efficient resource allocation. Figure 6 illustrates where a CBA enters the risk management process.

![Diagram showing the position of a CBA in a risk management process.](Adapted from Mattsson, 2004)

Figure 6. The position of a CBA in a risk management process. From Problem detection to implemented measure. (Adapted from Mattsson, 2004)

Applied welfare economics is the theoretical foundation for the CBA (Farrow and Viscusi 2011). It was born out of the utilitarian ideology aspiring to make public decisions that generate the highest social welfare, although the constraints of a budget function means that we are always faced with limited resources.

There are two types of CBA, the ex-ante CBA which assists decisions on whether public resources should be allocated to a specific project or policy, and the ex-post CBA which calculates the efficiency of the same when a policy or project is implemented. It can serve as a learning tool for academia, managers, politicians etc. about the efficiency of interventions (Boardman et al. 2014). What we usually mean when
we talk about CBA is the ex-ante CBA. This is also the approach further discussed here.

CBA as a tool for flood risk management is not a new phenomenon. In the 1930s USA, the government wanted a broader social motivation for measures and interventions against floods, and in 1936 the US Flood Control Act was implemented, which required the use of CBA to reduce private construction of ineffective levee buildings and to reduce pork barrel politics (Wiener 1996). The modern CBA is considered to have been born in the US in the 1950s, and in the 1980s CBA were made mandatory in the US in decision-making processes regarding public expenses and legislation that have considerable effects on the economy or are expected to be very costly (Mattson 2006). In the 1960s other countries started to adopt the CBA framework as a decision support tool and the area of application spread to projects pertaining to health, environment, education, labor market measures etc. Despite the early application of CBA in the flood risk management in the US, this has not been the case in Sweden. CBA is not mandatory in public investments in Sweden. The Swedish Transport Administration was the first organization in Sweden to adopt and apply CBA in analyses of public welfare in road projects. This was in the middle of the 1960s. Since the beginning of the 1990s the Swedish Civil Contingencies Agency have played an important role in implementing CBA in other areas of public health and safety in Sweden, mostly within fire safety and rescue service actions by publishing large numbers of reports and textbooks on the subject. Although applied within certain areas at government levels, it is not systematically implemented in the decision-making process concerning public resources in Sweden on any national, regional or municipal level. CBA have not been a standardized approach in natural hazard risk management in Sweden. It is considered to be time consuming, complex and to require expert knowledge (SKL 2009).

The optimal CBA-scenario would be to include all cost and benefits related to a set of appropriate risk-reducing projects and then choose the project which delivers the highest benefit-cost ratio (assuming that this project achieves the estimated risk reduction and assuming that the distribution of the costs and benefits is considered accepta-
ble). Most common, however, are the inclusion of direct tangible damage to residential property (Tate et al. 2015, Meyer et al. 2013, Smith and Ward 1998). Damage to residential areas therefore very much influences estimation of the benefits related to risk reduction measures. The most frequently used approach to estimating direct tangible damage is utilizing damage functions that express the cost of damage inflicted upon an object as a function of one or more damage inducing factors (Meyer et al. 2013). Such damage function have, prior to this thesis, not been derived for Swedish hazard scenarios.
5. Results

This section presents the main results and the conclusions of the 4 different studies of the thesis. For complete information of the studies, see the full text papers in the appendix.

5.1 Flood damage in Sweden 1987-2013

The aim of the study was to analyse the Swedish flood damage trend using insurance payouts caused by flood damage to residential property, extreme rainfall, GRP per capita, and housing stock, and to evaluate the availability and applicability of existing data for such analysis.

5.1.1 Data availability and applicability

Number of payouts per year is extracted from the Länsförsäkringar database for the years 1987-2013. Only 19 of the 21 Swedish counties could be analysed. Information on extreme precipitation was provided by SMHI, and socioeconomic information was available at Statistics Sweden.

There are several challenges related to the availability of flood exposure data. It belongs to the nature of extreme events that they are rare and thereby generate only a limited number of events to analyse. Further, there are challenges related to using data that have been recorded as well, both concerning accessibility and the spatial and timely limitation in the documented data. One of the obstacles when analyzing variations in damage trends is to successfully combine the different data sets. A reason for this can be, for example, that input variables have different limitations, both spatially and in time. One example from this study was that insurance data was available for the years 1987-2013 while data on numbers of extreme rainfall events per year were available only for the time period 1996-2013. Further, information on housing stock with applicable spatial resolution to match the other variables was available only for the years 1990-2011. Such mismatch in the overlap of data length is not uncommon but shortens the length of the time series available for analysis and thereby also the number of observations that can be used to identify and estimate ef-
fects of time variant variables on damage trends. Combining the above mentioned variables at national scale, only allowed for analyzing a time series of 16 years (1996-2011), as compared to the length of 27 years of insurance data available.

Another data limitation related to the insurance data is the spatial classification of damages made by the insurance companies. It limits the options of using explanatory variables representing local or regional flood vulnerability factors that can further increase knowledge of flood risks. This spatial limitation especially applies to factors describing drainage system capacities, topographic characteristics, e.g. slope index, and also limits the possibility of more accurately relating precipitation characteristics to damage location.

5.1.2 Causal relationships - exposure and vulnerability

The number of payouts varies considerably between years but the estimated regression line in Figure 7 shows an increase in the number of payouts per year during the 27 year period (1987-2013) of data available to this study.

![Insurance payouts per month (%) 1987-2013](image)

*Figure 7. Number of payouts per year aggregated at national level, 1987-2013, and monthly distribution of insurance payouts presented as percentage of total number of payouts for the time period 1987-2013.*
The results of four time series cross sectional regression models are presented in Table 4: a Poisson FEM, a Poisson FEM with cluster robust standard errors, a negative binomial FEM, and a negative binomial regression with county dummies.

The regression coefficients are expressed as incident rate ratios (IRR). Values higher than 1 implies increasing effects on mean number of insurance payouts and estimates lower than 1 would imply a decreasing effect.

The climate change related variable, **extreme**, is found to be highly significant in all four models. When **extreme** increased with one extreme rainfall event per year, the estimated number of yearly damages increased by 5-15 percent, under the assumption that other variables are kept constant. The Negbin model with county dummies modeled the highest effect estimating a 15 percent increase if **extreme** increased by one event. The Poisson FE model and Poisson FE, robust estimates increased with 10 percent, followed by the Negbin FE, estimating a 5 percent increase of damages if extreme rain increased by one event.

**GRP per capita** was found to be significant in two models. The Poisson FE estimated an increase in GRP per capita by 1,000 SEK to have affected the number of yearly damage only by 0.3 percent, keeping other variables constant. The Negbin FE gave similar results estimating an increase of 1,000 SEK to have affected the number of yearly damages by 0.2 percent.

Number of **dwellings** per year were similar to GRP per capita, significant in the two models Poisson FE and Negbin FE. The Poisson FE estimated the effect of one more building being built per year to have affected the number of residential damage by 0.0008 percent. The Negbin estimated this effect to 0.0002 percent. This effect can be considered to be negligible, but it must be taken into account that this effect is measured in relation to the increase of one more building per year.
Assuming that *dwellings* increase damages by 0.0008 percent per new building per year, 6250-18750 new building per year must be built to have the same effect as the effect of one extra extreme rainfall per year (5-15%).

The Swedish board of housing, building and planning have estimated that the demand for new housing in Sweden amounted to approximately 600 000-700 000 between the years 2012-2025 (Boverket 2015, SVT 2016). The highest demand for new housing is in already urbanized areas. According to Boverket (2016), 64 000 dwellings were built in Sweden during 2016 and 67 000 dwellings will be built in 2017. If the Swedish citizens’ demand for residential buildings is to be met during the next decade, insured damage trends can be expected to continue increasing, irrespective of extreme rain or not. Increased future vulnerability caused by the combined changes to precipitation patterns and housing stock can create an increased vulnerability to residential areas that should be taken seriously, not only by government actors but by scientist, practitioners and individuals as well.

5.1.3 Application of results in quantitative assessment

The results of this study emphasize the need for natural hazard risk assessments to account for a short term local perspective including changes in risk caused by e.g. housing stock growth and population growth, as well as a long term global perspective of climate change mitigation affecting extreme precipitation patterns.
Table 4. Result of regression analysis. Dependent variable: Damage (number of claims paid by the insurance group during summer on a yearly basis). Estimated coefficients and standard errors (in brackets) are expressed as incident rate ratios (IRR).

<table>
<thead>
<tr>
<th></th>
<th>Poisson FE</th>
<th>Poisson FE, robust</th>
<th>Negbin FE</th>
<th>Negbin/county dummies</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Intercept</strong></td>
<td>0.2433874*** (0.0680187)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Extreme</strong></td>
<td>1.101643*** (0.0029934)</td>
<td>1.101643*** (0.0325263)</td>
<td>1.0465757** (0.173496)</td>
<td>1.152838*** (0.0338134)</td>
</tr>
<tr>
<td><strong>GRP per capita</strong></td>
<td>1.00275*** (0.0002273)</td>
<td>1.00275 (0.0020309)</td>
<td>1.00226* (0.0010378)</td>
<td>1.00147 (0.0017645)</td>
</tr>
<tr>
<td><strong>Dwellings</strong></td>
<td>1.000008*** (0.0000002)</td>
<td>1.000008 (0.0000222)</td>
<td>1.000002* (0.000000952)</td>
<td>1.000023 (0.0000245)</td>
</tr>
<tr>
<td><strong>Alpha</strong></td>
<td></td>
<td></td>
<td></td>
<td>1.368374</td>
</tr>
<tr>
<td><strong>Log-likelihood</strong></td>
<td>-10854</td>
<td>-10854</td>
<td>-1258</td>
<td>-1372</td>
</tr>
<tr>
<td><strong>Number of observations</strong></td>
<td>304</td>
<td>304</td>
<td>304</td>
<td>304</td>
</tr>
</tbody>
</table>

*** P<0.001, ** P<0.01, * P<0.05
5.2 Damage assessment of lake floods
The aim of the study was to use available exposure and damage data to identify and estimate causal relationships between lake floods and extent of direct damages to residential areas, and to evaluate its applicability for deriving damage functions and for flood risk assessments. The results of the study rest upon case studies of exposure and vulnerability of the extensive and prolonged flooding along Lake Vänern and Lake Glafsfjorden in south of Sweden, from autumn 2000 until spring 2001.

5.2.1 Data availability and applicability
Information on lake levels was compiled in GIS using data obtained from Arvika municipality regarding Lake Glafsfjorden and from the Swedish Meteorological and Hydrological Institute (SMHI) for Lake Vänern. The data from SMHI also contained data on wind conditions. Elevation data for affected shore areas were extracted from the Swedish National Elevation Database. The data consisted of a grid of 2x2 m cell size with a vertical accuracy of approximately 5–20 cm. Damage data were provided by Länsförsäkringar Värmland. Concerning spatial resolution, the insurance company provided information about the municipality in which the damage occurred, but did not have information on the exact location of the flood-damaged property. There was also a large deviation on the detail level of the flood damage documentation in the insurance reports, which could be traced back to the effort of the individual insurance adjuster. Due to incomplete information on exact location, damage-reducing measures, age of building and the number of floors, telephone interviews were carried out directly with the afflicted policyholders. Because of the time elapsed since the event (12 years), some house owners had only vague recollections of the specific characteristics of the flood and the flood damage. Some insurance holders could not be reached due to lack of current contact information and some had passed away. The step to link the reported insurance payments with the GIS layer for buildings was not as straightforward as anticipated and some cases could not be localized with certainty. Out of the 427 observations on individual insurance claims initially provided by the insurance company, a dataset
of 195 observations contained enough information to undertake further analysis of property exposure and vulnerability to lake floods.

5.2.2 Causal relationships – exposure and vulnerability

The different factors that could be quantified and included in regression analysis were water levels (cm), distance to water front (m), duration (weeks), if buildings were built prior to the Second World War, whether the building had more than one floor, if private damage reducing measures were taken, and whether there was building damage or only damage to inventories.

43 percent of the observations in the sample occurred in a fringe area never reached by surface water. Damage costs in fringe areas were lower than in areas exposed to surface water flooding, but contributed to raising the overall costs of the events. Sixty percent of the insurance claims in the study concerned structural damage to buildings. Private damage-reducing measures were carried out for 43 percent of all property in the case study area. Home owner initiative to implement private damage-reducing actions decreased the probability of building damage by 38.5 percent. Actions that were taken included building barriers, hire or buy water pumps, hire transport and storage for movable inventory, artificial elevation of buildings or a combination of two or more of the these measures.

The results of the multiple linear regressions that estimated the effects risk factors had upon the size of insurance payments, are summarized in Table 5.

Lake water levels were statistically significant only in 1A (full sample) and 1C (only holiday houses), and the increase in damage amounts that could be related to increased lake water levels was small (0.6 percent and 1.1 percent respectively per cm increased lake water level). Distance to waterfront had a significant effect in all groups except for 1C and 2C (holiday houses). The size of insurances claims decreased with 1.9-2.6 percent when distance to lake water increased with one unit (m). The effect was highest for detached houses.
The duration of the floods ranged from zero weeks up to 27 weeks, with a mean duration of 3 weeks. Duration was statistically significant only in subgroup 1B (detached houses). When the duration of the flood increased by one unit (week) the size of the mean insurance payment increased by 16.9 percent.

Thirty-six percent of the damaged objects were built in 1945 or earlier and are henceforth referred to as pre-war buildings. The pre-war variable is significant in the full sample and for detached houses but not for holiday houses. Buildings built prior to the end of World War II yield 52 percent lower mean insurance payments compared to that of post-war buildings.

Out of 63 detached houses, 31 had basements, 15 had no basement and for 17 houses there was no information. Overall, only 16 percent of the buildings in the sample consisted of more than one floor. Having more than one floor was statistically significant for all groups except for those containing only holiday houses. The holiday houses in the samples were generally one-floor houses. Having more than one floor is related to increased insurance cost between 76-145 percent, keeping all other variables constant, with the largest effects in the sub-samples containing only detached houses (1B, 2B).

### 5.2.3 Application of results in quantitative assessment

The study yields valuable results concerning causal relationships between flood and building characteristics, and the decreasing effect that private risk reduction had on the probability of building damage. In section 4.4.1 water level is emphasized as the most significant predictor for flood damage. In this study lake water levels were only significant for houses close to the lake front (holiday houses and in the full sample) but the actual effect of increased water levels was low. Possible explanation for this is 1) marginal changes in water levels are not a good predictor for residential flood damage in Sweden, or 2) lake water levels are not a good proxy for water levels inside buildings.
The low practical significance of risk factors (except for private damage reduction) indicate that presently existing data are not appropriate to serve as the basis for empirical flood damage functions with the purpose of predicting future flood damage.

Table 5. Linear multiple regression analysis. Dependent variable: Insurance payments, robust standard errors in brackets.

<table>
<thead>
<tr>
<th>Explanatory variable</th>
<th>Full Sample (1A)</th>
<th>Detached houses (1B)</th>
<th>Holiday houses (1C)</th>
<th>Full sample (2A)</th>
<th>Detached houses (2B)</th>
<th>Holiday houses (2C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>8.024***</td>
<td>8.004***</td>
<td>7.665***</td>
<td>8.447***</td>
<td>8.737***</td>
<td>7.917***</td>
</tr>
<tr>
<td></td>
<td>(.246)</td>
<td>(.384)</td>
<td>(.290)</td>
<td>(.23)</td>
<td>(.636)</td>
<td>(.373)</td>
</tr>
<tr>
<td>Water level</td>
<td>.006*</td>
<td>-.013</td>
<td>.011**</td>
<td>.005</td>
<td>-.004</td>
<td>.009</td>
</tr>
<tr>
<td></td>
<td>(.003)</td>
<td>(.012)</td>
<td>(.005)</td>
<td>(.003)</td>
<td>(.013)</td>
<td>(.006)</td>
</tr>
<tr>
<td>Distance</td>
<td>-.019***</td>
<td>-.024***</td>
<td>-.006</td>
<td>-.024***</td>
<td>-.026***</td>
<td>.422</td>
</tr>
<tr>
<td></td>
<td>(.004)</td>
<td>(.005)</td>
<td>(.005)</td>
<td>(.005)</td>
<td>(.005)</td>
<td>(.012)</td>
</tr>
<tr>
<td>Duration</td>
<td>.03</td>
<td>.156*</td>
<td>.000</td>
<td>.014</td>
<td>.114</td>
<td>-.016</td>
</tr>
<tr>
<td></td>
<td>(.018)</td>
<td>(.070)</td>
<td>(.028)</td>
<td>(.026)</td>
<td>(.072)</td>
<td>(.004)</td>
</tr>
<tr>
<td>Damage to buildings</td>
<td>1.983***</td>
<td>2.216***</td>
<td>2.505***</td>
<td>1.795***</td>
<td>1.786**</td>
<td>2.541***</td>
</tr>
<tr>
<td></td>
<td>(.228)</td>
<td>(.367)</td>
<td>(.344)</td>
<td>(.277)</td>
<td>(.489)</td>
<td>(.444)</td>
</tr>
<tr>
<td>Pre-war</td>
<td>-.736**</td>
<td>-.728*</td>
<td>-.565</td>
<td>(.259)</td>
<td>(.348)</td>
<td>(.612)</td>
</tr>
<tr>
<td></td>
<td>(.251)</td>
<td>(.34)</td>
<td>(.525)</td>
<td>(.288)</td>
<td>(.423)</td>
<td>(.468)</td>
</tr>
<tr>
<td>Floors</td>
<td>.567*</td>
<td>.705*</td>
<td>.452</td>
<td>.785**</td>
<td>.897*</td>
<td>.118</td>
</tr>
<tr>
<td></td>
<td>(.251)</td>
<td>(.34)</td>
<td>(.635)</td>
<td>(.288)</td>
<td>(.423)</td>
<td>(.468)</td>
</tr>
<tr>
<td>Damage reduction</td>
<td>.773***</td>
<td>.91*</td>
<td>1.34***</td>
<td>.875***</td>
<td>.576</td>
<td>1.396***</td>
</tr>
<tr>
<td></td>
<td>(.213)</td>
<td>(.36)</td>
<td>(.295)</td>
<td>(.253)</td>
<td>(.536)</td>
<td>(.313)</td>
</tr>
<tr>
<td>N</td>
<td>195</td>
<td>57</td>
<td>69</td>
<td>132</td>
<td>39</td>
<td>47</td>
</tr>
<tr>
<td>Adjusted $R^2$</td>
<td>.3890</td>
<td>.5518</td>
<td>.5297</td>
<td>.4402</td>
<td>.5474</td>
<td>.4795</td>
</tr>
</tbody>
</table>

*** P<0.001, ** P<0.01, * P<0.05
5.3 Assessment of pluvial flood exposure and vulnerability of residential areas

The aim of the study was to identify and estimate causal relationships between pluvial flood exposure and the extent of direct damages to residential areas, and to evaluate the applicability of the results for flood risk assessment.

5.3.1 Data availability and applicability

A total of 49 different rainfall events and 2140 individual insurance payouts occurring in the months of June, July and August between the years 2000 and 2013 in 13 different municipalities were included in the analysis. The insurance data did not contain information that specified type of flood or how the water entered the building. Radar data were provided by the SMHI, and used to determine the amount and intensity of precipitation at the date, time of day and municipality where flood damage had occurred according to insurance records.

Data scarcity and inhomogeneity among data sets concerning spatial and temporal overlaps, hindered the statistical analysis. Overall, the data availability concerning pluvial flood damages and their corresponding risk factors are poor. This study underlines the importance of data availability, data quality, and detail level to enable quantitative pluvial flood risk assessment.

5.3.2 Causal relationships – exposure and vulnerability

Residential damage at object level

Models 1, 2 and 3 analysed insurance payouts at object level. The results are presented in table 6. Effects on size of damage costs for moveable property (model 1) were estimated using the following variables: intense rain events, aggregated daily precipitation the day prior to damages, and rainfall occurring during the day. These three explanatory variables were all statistically significant. The mean value of insurance compensation for intense rain was 42 percent higher than payouts for less-intense rainfall events. The occurrence of rain the day
prior to damage observations decreased the insurance payout by 0.03 percent for every mm of rain the previous day.

Effects on size of damage cost for building damage were estimated using the following variables: intense rain events, aggregated daily precipitation, aggregated daily precipitation the day prior to damages, rainfall occurring during the day/night, and rainfall exposing central urban areas of the municipality.

Intense rain events had a significant effect, increasing the mean size of payouts by 92 percent compared to those resulting from less-intense rains. The occurrence of rain the day prior to the damage event decreased insurance compensations by 0.2 percent for every mm of rain the previous day.

Rain-exposed residential houses in central urban areas of the municipality showed a 69 percent increase in mean insurance compensations for individual damages compared to rainfall-exposed residential houses in less central and urban parts of the municipality. Properties exposed to rain during the night received 43 percent higher insurance compensations than those exposed to rain occurring between the hours of 06.00-24.00.
Table 6. Regression results. The dependent variable is the natural logarithm of the size of insurance compensation for damage at object level. Standard errors are in brackets.

<table>
<thead>
<tr>
<th>Explanatory variables</th>
<th>Model 1 Ln MOVINSURE</th>
<th>Model 2 Ln DETACHINSURE</th>
<th>Model 3 Ln DETACHINSURE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>9.413*** (0.122)</td>
<td>10.041*** (0.148)</td>
<td>10.136</td>
</tr>
<tr>
<td>PRECIPDAILY (mm)</td>
<td>–</td>
<td>–</td>
<td>-0.0004 (0.0016)</td>
</tr>
<tr>
<td>INTENSE (binary)</td>
<td>0.35** (0.121)</td>
<td>0.65*** (0.168)</td>
<td>–</td>
</tr>
<tr>
<td>PRECIPPRIOR (mm)</td>
<td>-0.003** (0.001)</td>
<td>-0.002* (0.001)</td>
<td>-0.002* (0.0011)</td>
</tr>
<tr>
<td>DAY (binary)</td>
<td>-0.349*** (0.077)</td>
<td>-0.273* (0.103)</td>
<td>–</td>
</tr>
<tr>
<td>NIGHT (binary)</td>
<td>–</td>
<td>–</td>
<td>0.5234*** (0.103)</td>
</tr>
<tr>
<td>URBEXPOS(binary)</td>
<td>–</td>
<td>–</td>
<td>0.3568** (0.1216)</td>
</tr>
<tr>
<td>POPDENS (per m^2)</td>
<td>–</td>
<td>-0.00006 (0.0001)</td>
<td>-0.0001 (0.0001)</td>
</tr>
<tr>
<td>N</td>
<td>1116</td>
<td>1124</td>
<td>1036</td>
</tr>
<tr>
<td>R^2</td>
<td>0.03</td>
<td>0.03</td>
<td>0.05</td>
</tr>
</tbody>
</table>

*** P<0.001, ** P<0.01, * P<0.05

Residential damage aggregated at municipality level

This section analyses the effects of aggregated maximum daily amounts of rain, rain intensity, urban exposure, population density and the number of payouts made by the insurance industry upon the total aggregated compensation paid by insurance companies to residents for flood damages using two different models, models A and B. The results are presented in Table 7.

Aggregated daily precipitation did not have a significant effect upon the total sum of insurance compensations. Neither did the categorical variable of urban exposure, which represents rainfall occurring in the central parts of a municipality, nor did the population density variable.
Intense rainfall, which added a time element to the rain amounts, had a statistically significant effect on the total sum of insurance compensations per rainfall (model B). Rainfall events that were categorized as intense in this study caused the total sum of insured property losses to be higher than for less intense rain events. The mean aggregated insurance compensation was 192\(^3\) (coeff. 1.072) percent higher for intense rain.

Number of payouts had a significant effect on the size of aggregated insurance payouts, meaning that the total amount compensated by the insurance industry increased when the number of individual insurance payouts increased (model B). Figure 8 displays the relationship between aggregated insurance compensations at municipal level and the number of payouts at municipal level per rainfall in relation to intense and non-intense rainfall events.

5.3.3 Application of results in quantitative assessment

Despite high statistical significance of damage influencing variables, they all had low practical significance on the actual size of mean damage cost. The R\(^2\) values of the models (models 1-3) are very low, explaining only 3-5 percent of the total variation in insurance compensations. This means that the largest part of flood damage costs at object level, both to buildings and moveable property, are related to variables that have not been possible to quantify on the basis of the available data set. In their current state, the models are not suitable for making inferences on the size of insured losses to residential property at object level. The discontinuity and the heterogeneity of different datasets (damage data versus precipitation data) leave very few possibilities for deriving residential flood damage functions in a Swedish (or similar) pluvial flood context.

The R\(^2\) value for model B, however, was 0.57, meaning that 57 percent of the total variation in aggregated insurance compensation in the sample could be explained by a model containing information on the

\[3 \text{ The percent change from the estimated coefficient is } (e^{(1.072)} - 1) \times 100 = 192 \% \]
expected number of payouts and the expected share of intense rain-falls. This means that mean damage cost can be multiplied with expected number of damaged properties to give some guidance when estimating benefits of pluvial risk reduction to residential areas.

Figure 8. Aggregated flood damage at municipal level. Actual and estimated relationship between LN (aggregated insurance compensations) and number of payouts (refunds) per municipality, with 95% confidence interval. Left side picture represents normal rain, middle picture represents intense rain, and right side picture represents all rain.

4 Leaving number of payouts out of the model gives and $R^2$ value of 0.35.
Table 7. Regression result. The dependent variable is the natural logarithm of the estimated aggregated insurance compensations at municipality level. Standard errors are in brackets.

<table>
<thead>
<tr>
<th>Explanatory variables</th>
<th>Model A Ln AGGINSURE</th>
<th>Model B Ln AGGINSURE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>13.604***</td>
<td>13.261***</td>
</tr>
<tr>
<td></td>
<td>(0.349)</td>
<td>(0.280)</td>
</tr>
<tr>
<td>PRECIPDAILY, mm</td>
<td>0.005</td>
<td>_</td>
</tr>
<tr>
<td></td>
<td>(0.005)</td>
<td></td>
</tr>
<tr>
<td>INTENSE (binary)</td>
<td>_</td>
<td>1.072***</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.323)</td>
</tr>
<tr>
<td>URBEXPOS(binary)</td>
<td>0.493</td>
<td>0.372</td>
</tr>
<tr>
<td></td>
<td>(0.350)</td>
<td>(0.319)</td>
</tr>
<tr>
<td>POPDENS</td>
<td>0.0000</td>
<td>0.0001</td>
</tr>
<tr>
<td></td>
<td>(0.0004)</td>
<td>(0.0002)</td>
</tr>
<tr>
<td>PAYOUTS</td>
<td>0.005***</td>
<td>0.004***</td>
</tr>
<tr>
<td></td>
<td>(0.001)</td>
<td>(0.001)</td>
</tr>
<tr>
<td>N</td>
<td>49</td>
<td>49</td>
</tr>
<tr>
<td>R²</td>
<td>0.48</td>
<td>0.57</td>
</tr>
</tbody>
</table>

*** P<0.001, ** P<0.01, * P<0.05
5.4 Quick clay landslides and loss of lives
The aim of the study was to use existing data to explore and identify the causal relationship between quick clay landslides and loss of lives and to evaluate the applicability of the results in quick clay landslide assessments and for deriving fatality curves.

5.4.1 Data availability and applicability
The dataset used in this study contains data from 66 landslides collected from two data sources. The data of 55 quick clay landslides that occurred between 1848 and 2009 were extracted from one of the two sources, the Norwegian landslide database Skrednett. The documentation quality of Skrednett is, according to Jaedicke et al. (2009), strongly influenced by the personal engagement of local observers and observational routines. Despite these uncertainties, it is seen as a unique source of statistical analysis (Jaedicke et al. 2009). The remaining 11 landslides were extracted from the second source, the Swedish natural hazards information system (MSB 2016). The landslides in Sweden occurred in a shorter time period, 1950 to 2006.

Human beings were exposed in 52% to 62% of the landslides, and people died in 27% of them. The number of people exposed overall, summing up all the landslides in the sample, was between 734 and 1594. Overall, 167 people lost their lives in the 66 landslides, yielding an average landslide fatality rate of 2.5. One landslide event stood out, this was the Verdal landslide in Norway in May 1893. It occurred at night-time in Verdal in Northern Tröndelag killing 116 persons of the 250 persons exposed to the landslide.

The amount of information available from historical information varied between the observations in the sample. For some quantitative information (e.g., time of day, warning signs, building characteristics, cause of death, physical ability, and age of the exposed population), the informational value of the dataset was very limited. We found that potential risk factors such as country, year, and number of people exposed were the only risk factors in the sample set adequately documented to serve as input data to the statistical analysis estimating loss
of life functions and the derived loss of life estimates were functions of the number of exposed persons.

Records of historical events are one of the few sources at hand for evaluating the actual fatality risk, and despite uncertainties, they can contribute valuable information when assessing and communicating landslide risk. Concerning availability and quality of quantifiable damage and loss information in the Nordic historical records, with respect to statistical inference, the data sample set was limited. One known way of circumventing this barrier can be to transfer values derived from other studies in other countries with quick clay deposits (e.g. Canada and Russia), or for other types of landslides. Based on our results, however, fatality rates obtained for other types of landslides can probably not be applied to quick clay landslide risk assessments.

5.4.2 Causal relationships – exposure and vulnerability

The study found a statistically significant positive relationship between the number of people exposed and fatalities, meaning that the number of fatalities increased when more people were exposed. This relationship is less strong when the outlier (the Verdal landslide) is excluded. The variable for representing whether the landslide occurred in Norway or Sweden was not statistically significant in three of the four tested models. This indicates that there are no significant differences in fatalities for Norwegian and Swedish landslides. We can therefore merge the data from the two countries. The coefficient representing year of occurrence is negative, but not statistically significant, meaning that we cannot conclude that the number of fatalities in the analysed time period has decreased.

5.4.3 Simulation of fatality curves

The Monte Carlo simulation accounts for the uncertainty in the number of exposed humans. In the OLS model (model 3), the risk of fatality increased linearly by 0.18 for each additional person exposed if the Verdal landslide is included; it increases only 0.02 if it is excluded. The count data models (model 4) are non-linear as can be seen from the predicted values shown graphically in Figures 9 and 10.
Figure 9 shows observed data, the average statistic, (i.e. 0.16) and the predicted values using all observations (including the Verdal landslide) for the OLS and the negative binomial models. It illustrates that the OLS model yields a result very similar to the average. The count data model, on the other hand, predicts a non-linear relationship between numbers of people exposed and expected fatalities. When few people are exposed, or when around 250 people are exposed, the linear and non-linear models predict the same number of fatalities. However, between these values, the linear models overestimate the number of fatalities. Note that the SGI data values shown in figure 9 are the numbers SGI assumed to be the most probable numbers of people exposed, and not necessarily actual number of exposed human beings. The simulated observations used in the estimation of the models are not shown. However, the curves are drawn from the predicted values using the models with simulated data.

Figure 10 shows observed data, the average statistic, and the predicted values excluding the outlier, the Verdal landslide, for three models applied to the Monte Carlo simulated data. Figure 10 also shows the spread of the simulated observations. The negative binomial model and the OLS model are similar, which means that the count data model predicts relationships that are nearly linear up to 200 exposed people. By removing the outlier, fewer fatalities are predicted. However, the graph of the negative binomial regression model only considering up to twenty people exposed, shows that the risk of fatality is increasing more, compared to the models including all observations. This model predicts even more fatalities than the average value used by SGI. Figure 10 therefore shows that it may be reasonable to use different fatality curves depending on the number of people exposed.
Figure 9: Observed and predicted values. The SGI data values are the most probable number of people exposed according to the Swedish Geological Institute (SGI). The average is the average loss of life rate based on SGI’s observed values of exposed persons. The predicted values (Models 3a and 4a) are calculated from the estimated models using the Monte Carlo simulated data, which consider the uncertainty in number of exposed persons.

Figure 10: Observed and predicted values excluding the Verdal slide. The SGI data values are the most probable number of people exposed according to the Swedish Geological Institute (SGI). The average is the average loss of life rate based on SGI’s observed values of exposed persons. The predicted values (Model 3b, 4b and 4c) are calculated from the estimated models using the Monte Carlo simulated data, which consider the uncertainty in number of exposed persons. The spread in uncertainty is also shown by the horizontal dotted line called “simulated observations”.

54
5.4.4 Application of results in quantitative assessments

Derived quick clay fatality curves can serve as policy guidance concerning quick clay risk reduction. The results imply that loss of life increases exponentially with the size of the exposed population, but also that there might be different subsets of loss of life distributions with individual slope gradients depending on the size of the exposed population. Previously, in Sweden, a mean fatality index has been applied to risk assessments (SGI 2011). Our results imply that this approach overestimates the number of fatalities when the number of exposed individuals is between 20 and 250, underestimates it when the number of exposed individuals is high (over 250), but also underestimates it for under 20 people exposed. Probably, diversified loss of life curves, accounting for the size of the exposed population, may be more appropriate to apply. This should be taken into account by policymakers when deciding on risk reducing policy measures. I do recognize that using exposure as the only risk factor is a simplification of complex scenarios and that it can explain only a limited part of human vulnerability to quick clay landslides slides. However, it also contributes important quantitative information to ex-ante analysis aimed to guiding policy decision on risk reduction.
6. General discussion

Natural hazard damages have increased worldwide (IPCC 2012). Impacts caused by hydrological and meteorological hazards have increased the most (Fig. 1). When analyzing insurance payouts for Sweden, I have found that flood damages have been increasing in Sweden as well (Fig. 7). With climate change and increasing populations we can expect this rapidly growing trend to continue unless efforts are made to reduce risk and adapt communities to the threats.

The overall objective of this thesis was to improve the conditions for using quantitative decision support tools in natural hazard risk assessments. The specific aims was to identify and estimate causal relationships between hazards, exposure and damage, and to evaluate the applicability of systematically collected data sets to produce reliable and generalizable quantitative information for decision support. Damage categories differ in their vulnerability to hazards and also in quantification approach. Different damage categories must therefore be estimated separately and then summarized (Seifert et al. 2010).

Figure 11. Information on hazard exposure and hazard vulnerability make up the foundation for damage quantification and cost estimation and thus for the economic decision support tools.
Figure 11 is a pyramid illustrating the importance of data availability and quality. Damage quantifications and the risk factor estimates are no better than the data on which they are founded, and hence their quality determines the reliability of the estimates. In section 4 I emphasized the interdependencies of the damage function, the risk equation, CBA-analysis and the risk management process (fig. 4). The quantification of damages is an essential input to a risk assessment. An economic analysis of risk reduction is then only as reliable as the input data it rests upon and therefore the data make up the very foundation of economic analysis. If the foundation it rests on is poor, then the economic decision basis is poor.

Concerning the methods applied to analysis of damage data, Meyer et al. (2010) claims that the methods used for hazard damage estimations are usually crude. By knowing which methods and models that have been possible to apply in the four studies in this thesis, I agree with their reasoning but insists that as long as data are crude, sophisticated estimation methods are unfeasible and redundant. Reliability of natural hazard damage estimates cannot be improved only by applying complex methods if the input data do not match the assumptions of the models. I claim that the amount and the properties of available data decide the detail level of the models to be estimated and also how adjustable the models are to applied risk management.

Data availability, homogeneity and reliability are large issues when analyzing natural hazard damages in Sweden. In the absence of large, systematically collected datasets, using what is available is the only option to creating knowledge concerning causal relationships. This thesis has established causal relationships between residential exposure and flood damage. It has also established a causal relationship between the number of people exposed to quick clay landslides and fatalities. Main results concerning causal relationships between exposure and damage are listed below.

- The size of the exposed population had a significant effect on the probability of loss of life when exposed to quick clay landslides
– Increasing water levels increased the probability of lake flood damage
– Private damage-reducing actions decreased the probability of building damage with almost 40 percent
– Damage decreased as distance to the lake waterfront increased
– Lake floods of longer duration increased flood damage
– Prewar houses suffered lower lake flood damage
– Intensity of rain affects pluvial flood damage to a larger extent than the aggregated daily amount of precipitation.

At the same time, however, this thesis also shows that there is much we do not know about the causal relationships since the identified relationships can only explain small parts of the total variation in the damage data sets. This is a strong motivation to keep pursuing the identification of risk factors and their effect on society.

To the question of whether the presently available data are adequate for quantifying landslide and flood damages or not, the answer is ambivalent. The types of damage addressed in this thesis, i.e. flood damage to residential buildings and loss of lives due to landslides, can to some extent be quantified but not fully explained. This means that the extent of damage is documented but problematic to analyse. Reasons why certain objects and individuals suffer extensive damage while others only experience minor impacts are still uncertain. Previous research has identified the risk factors that may affect the vulnerability of exposed humans and objects (e.g. Agrawal et al. 2013, Meyer et al. 2013, Jongman et al. 2012, Merz et al. 2010, Messner et al. 2007). The effects of many of these factors were not possible to test statistically in a Swedish context because of inadequate information or incompatible types of information.

From the historical information in the landslide databases, I conclude that factors such as country, year and number of exposed people, were adequately documented to serve as input data to the statistical analysis estimating loss of life functions. The potential for improving the quantitative intangible damage information concerning old landslides is very limited. The information already gathered for old landslides in historical records has been highly dependent on the commitment and
involvement of a few historians (Jaedicke et al. 2009). For future documentation there are improvements that can be made in the aftermath of disasters. The priority during disasters is of course to save lives and to minimize damage, but when the crisis is over the involved organizations should be debriefed concerning both hazard characteristics and damage characteristics and this information should be added to other previous events in order to keep developing the information base for the benefits of future natural hazard management.

In studies 1, 2, and 3 information on the payouts made by Sweden’s largest home insurance group represented residential flood vulnerability. Direct tangible damages are viewed as the most “visible” types of hazard damages. It is, however, important to emphasize that visible does not necessarily mean well documented. The insurance companies’ damage databases are the most structured flood damage information source in Sweden. It is not, however, publicly available for risk assessment purposes. Concerning detail level of damage data, the actual insurance payouts did not reveal much about the circumstances surrounding the damaging event or the damaged objects and therefore the information needs to be supplemented by information on flood and weather characteristics, topography, building characteristics and characteristics of the property owner, in order to provide meaningful information to risk managers.

Flood and weather characteristics, land elevation information, and socioeconomic information could be extracted from government agencies and applicable information was also offered by one municipality (Arvika). Study 2 was the only study that could account for any building and homeowner characteristics. Information about the characteristics relied on the documentation efforts of individual insurance handlers. Information was also gathered by interviewing residents and home owners, relying on their memory of past events that occurred more than a decade prior to the interviews.

Extracting the information from the different sources was extremely time-consuming. The information gathered were not homogeneously structured and needed to be handled manually before entering the data into GIS or statistical software packages for further analysis.
Such data collection and data matching processes are cumbersome and loss of observations is not unusual which further complicates the statistical estimation process. At the start of study 2, there were 427 insurance compensation observations available for analysis. During the process of supplementing these observations with information on risk factors, potentially affecting the damage outcome, the number was reduced to 195 observations. Similar challenges were also experienced in the other studies.

In section 4 (Fig. 4) I emphasize the interdependencies and the interconnections between damage functions, the risk equation and the quantitative risk assessments independent of whether the assessment was performed as a part of a CBA, a risk management process or both. This was done to highlight the importance of damage data and its role in the risk outcome. The interlinkage between the different parts can be summarized as follows: Damage data and data on potential risk factors are essential to establish causal relationships between hazard and damage. The damage function represents the vulnerability of objects when exposed to a hazard and estimates the extent of damage (E x V) and should be based on scientifically motivated assumptions. Damages are related to hazard probabilities in the risk equation. The outcome of the risk equation is the quantitatively estimated magnitude of hazard risk, which is the desired goal of a quantitative risk assessment.

When performing a quantitative risk assessment for a certain hazard and set of impacts, it does not have to be performed separately. In fact, the steps to assess potential impacts overlap. Both frameworks require that impacts be identified and the size of the impacts analysed in order to establish magnitude of risk. In a quantitative risk assessment this means quantification of impacts. The CBA also requires that all impacts be monetized henceforth for comparison with costs of risk reduction. Monetization is not a necessity for a quantitative assessment in a risk management process, but since impacts are quantified this means that they are measured in some kind of unit, whether in terms of the number of exposed individuals, size of impacted area, number of exposed houses, system capacity loss etc. The Risk management framework, however, allows for a combination of qualitative
and quantitative approaches. One of the main criticisms of CBA framework is that impacts that are complicated or time-consuming to quantify are rarely included (Gamper et al. 2006, Mattsson 2006). In CBA literature, however, it is specified that impacts identified but not quantified are to be highlighted and discussed in line with quantifiable impacts (e.g. Mattsson 2006). This challenges the formulation of the decision support, but transparency in risk assessment is important regardless of whether it is a part of CBA or follows a ISO standard risk assessment.

For countries like Sweden, which do not have a responsible authority for framing, collecting and merging data concerning precipitation, floods, damages, technical systems, demographics etc., risk assessors at all levels are left with relying on sporadic and unsystematic data documented by different private and public organisations. More efforts are needed to identify and quantify the risk factors with the largest impacts on damages in order to derive meaningful quantitative risk assessment tools for risk reduction policy purposes. But even if the concerned organizations should start to systemize and organize their hazard and damage documentation from now on, it will take time to generate an adequate amount of data to derive reliable empirical damage functions for different impact categories because of the rarity of hazards.

Roger M. Cooke (2009) said: “Risk is a wily adversary, obliging us to relearn the same lessons over and over again”. I would say that we should learn from the experience of other nations and realize when it is time to change path. It has taken decades for other nations to reach their level of quantitative natural hazard risk assessment (e.g. Germany and USA), and despite their efforts many uncertainties still remain in their damage estimates.

The increased focus on the economic efficiency of risk reduction, however, demands quantitative approaches (Jongman et al. 2012). It has become apparent in this thesis that quantitative risk assessment and damage functions rely on a significant amount of input data, data that are not available in Sweden. Our options for the future needs to be further explored. One option is to synthetically derive flood dam-
age functions. Another option is to adopt damage functions derived for other countries. Importing damage functions/estimates derived elsewhere have been seen as an easy solution for countries and regions with limited data availability, experience, and other resources, since it has been regarded as the least data demanding, least expensive and least time consuming option for performing quantitative damage analysis in residential areas (Nastev & Todorov 2013, Jongman et al. 2012, Albano et al. 2015). Transferability of models to other geographical regions is, however, still a major gap in flood damage modeling (Hasandzadeh Nafari et al. 2016, Albano et al. 2015). Flood damage estimation without adapting to local conditions and without validation can result in inaccurate prediction of losses and thereby raise the uncertainty in flood damage assessments (Cammerer et al. 2013). Unsuccessful adaptation of damage functions can therefore lead to biased estimations and to misleading risk management guidance.

Another aspect to be aware of when striving towards developing damage function for decision support is the distributional aspect of risk reduction. Since hazard impacts are not distributed equally across society it is important for policymakers, risk managers and scientist to know that estimating damage impact by means of damage functions, does not explicitly consider distributional effects. Using a damage function to evaluate different risk reduction project in the same geographical area will not raise any equity concerns. Using one and the same damage function to estimate efficiency of, for instance, flood risk reduction in two separate areas of different socioeconomic class will raise equity issues. This is because the property of the affluent residents usually has a higher value and will then have higher impact in a CBA, for instance, leading to low income areas being less prioritized in an economic analysis. Concerning application of residential assets values in foreign damage functions, both replacement values, depreciated and not (Bubeck et al. 2011), and market values (de Moel & Aerts 2011) were applied. The insurance payouts used in studies 2 and 3 in this thesis can be categorized as depreciated replacement values.
Using average asset values or average damage values is a simple way of assigning values to objects at risk from hazards. This is the approach recommended in study 3 for estimating aggregated damage at municipal level when exposed to intense rain. The approach distributes the same value to all properties independent of their actual value or the social class of the occupants. Such a lower level damage function might be perceived as fair, but is still problematic due to the declining marginal value of income. An impact estimated at €1,000 damage might be of less concern to a wealthy property owner than to a low-income person. Residents belonging to higher social classes are also believed to be better equipped to handle economic shocks caused by hazards (Penning-Rowsell & Pardoe 2012). Distributional aspects are also relevant when comparing rural versus urban areas. Urban areas with higher property density will be more economically efficient to protect, especially if the residential damage function is the only representative of risk reduction benefits. In this thesis urban flood damages are overrepresented compared to rural flood damage and any results from this thesis must be applied with care to rural areas.

When a decision is driven by economic analysis (for example, a cost-benefit analysis), taking an overall economic efficiency to society into account, the distributional aspects are left to the decision maker. According to Penning-Rowsell and Pardoen (2012), however, distributional effects are rarely considered. In the literature reviewed for this thesis, equity, fairness and distributional issues are not at all addressed or only briefly touched upon (in for example Brouwer and van Ek 2004 and Davis 2016). For policy purposes, however, Meyer et al. (2013, 2014), among others, have recognized that it is important for policy formulation to know who suffers the most in the aftermath of a hazard.
7. Conclusion

The availability of systematically collected data for a quantitative assessment of loss of life caused by quick clay landslides and direct property damage caused by flood exposure in Sweden is generally low. With predicted increases in the frequency of heavy precipitation, there is an unmet need for quantitative support for risk reduction. This thesis concludes that the applicability of insurance data for quantitative risk analysis of residential areas at a disaggregated level in Sweden is low because of its insufficient detail level, both concerning spatial characteristics and object characteristics. If the detail level of the insurance data were to increase, it would have the potential of becoming highly applicable to scientific studies of natural hazard exposure and vulnerability, and as input to future flood risk analysis.

Reliable empirical residential flood damage functions at object level are not possible to develop in Sweden with the empirical data presently available. The time-consuming and cumbersome process of compiling, identifying, matching, discontinuous and heterogeneous datasets (e.g. damage data versus precipitation data) for estimating hazard vulnerabilities is a barrier to reliable flood damage assessment in Sweden.

If Sweden, and other countries in similar situations, are to improve their quantitative basis, focus could be shifted from empirical approaches to follow the lead of for example the UK, and develop synthetic approaches, by modeling object vulnerability for different damage categories based on firmly established and (empirically) tested assumptions. Available empirical data can then further be used to validate the functions and to adjust them to local conditions.

The risk factors identified in this thesis can serve as guidance to practitioners in risk assessments of future natural hazards. Presently, in the absence of more sophisticated and reliable models, information on insured damages on aggregated level can contribute valuable information to flood risk assessment and the economic analysis of risk reduction. It should, however, be applied cautiously and with awareness of its limitations. Further, I believe that the results of this thesis
can usefully serve as stepping-stones to further improvement of methods and models for quantitative natural hazard risk assessments.
References


Risk assessment of natural hazards

Natural hazard damages have increased worldwide. Impacts caused by hydrological and meteorological hazards have increased the most. An analysis of insurance payments in Sweden showed that flood damages have been increasing in Sweden as well. With climate change and increasing populations we can expect this trend to continue unless efforts are made to reduce risk and adapt communities to the threats. Economic analysis and quantitative risk assessments of natural hazards are fundamental parts of a risk management process that can support policymakers' decisions on efficient risk reduction. However, in order to develop reliable damage estimation models knowledge is needed of the relationships between hazard exposure and the vulnerability of exposed objects and persons. This thesis has established causal relationships between residential exposure and flood damage on the basis of insurance data. I also found that private damage-reducing actions decreased the probability of damage to buildings with almost 40 percent. Further, a causal relationship has been established between the number of people exposed to quick clay landslides and fatalities. Even though several relationships have been identified between flood exposure and vulnerability, the effects can explain only small parts of the total variation in damages, especially at object level, and more effort is needed to develop quantitative models for risk assessment purposes.