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# Review article: Assessing the costs of natural hazards – state of the art and knowledge gaps

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**Abstract.** Efficiently reducing natural hazard risks requires a thorough understanding of the costs of natural hazards. Current methods to assess these costs employ a variety of terminologies and approaches for different types of natural hazards and different impacted sectors. This may impede efforts to ascertain comprehensive and comparable cost figures. In order to strengthen the role of cost assessments in the development of integrated natural hazard management, a review of existing cost assessment approaches was undertaken. This review considers droughts, floods, coastal and Alpine hazards, and examines different cost types, namely direct tangible damages, losses due to business interruption, indirect damages, intangible effects, and the costs of risk mitigation. This paper provides an overview of the state-of-the-art cost assessment approaches and discusses key knowledge gaps.

It shows that the application of cost assessments in practice is often incomplete and biased, as direct costs receive a relatively large amount of attention, while intangible and indirect effects are rarely considered. Furthermore, all parts of cost assessment entail considerable uncertainties due to insufficient or highly aggregated data sources, along with a lack of knowledge about the processes leading to damage and thus the appropriate models required. Recommendations are provided on how to reduce or handle these uncertainties by improving data sources and cost assessment methods. Further recommendations address how risk dynamics due to climate and socio-economic change can be better considered, how costs are distributed and risks transferred, and in what ways cost assessment can function as part of decision support.

# 1   Introduction

## 1.1   Background

In times of increasing disaster losses (e.g. EM-DAT/CRED, 2012; IPCC, 2012; Munich Re, 2012) the reduction (or mitigation) of natural hazard risks needs to be effective and efficient. An in-depth understanding of the effects of disasters is required in order to develop forms of sustainable risk management as well as risk mitigation and adaptation[1] strategies (WB and UN, 2010; IPCC, 2012). This is especially true given the limited financial resources available. In this respect, reliable and comprehensive estimates of the costs and benefits of natural hazards are crucial for informed decision making and, more specifically, for the development of policies, strategies and measures to prevent or reduce the impact of natural hazards on societies and to improve their coping and adaptive capacities.

Cost assessments may be carried out in the aftermath of an event (ex post) or with regard to potential future events (ex ante). The aim of ex post assessments is to inform local or national governments of the overall amount of induced damage and to provide a basis for calculating levels of compensation and recovery support (e.g. Sächsische Staatskanzlei, 2003; McCarty and Smith, 2005; Karunasena and Rameezdeen, 2010). Ex ante cost assessments are conducted in order to support governmental decision making relating to alternative risk mitigation options (e.g. MAFF, 1999; BMLFUW, 2008a; BAFU, 2010). Decision makers in natural hazard risk management will want to consider, as far as possible, all the benefits and costs of alternative courses of action in the course of identifying the best available option. The insurance industry also has an interest in obtaining reliable cost figures so that it can calculate insurance premiums and financial worst case scenarios, i.e. the Probable Maximum Loss, or PML (e.g. Kleindorfer and Kunreuther, 1999; Woo, 2002a cited in Woo, 2002b; Smolka, 2006; Paudel et al., 2013).

Current methods for assessing the costs of natural hazards employ a variety of terminologies and methodological approaches relating to different hazards and sectors affected. For example, with regard to estimates of the aggregated and sector-based effects of disasters in the long term, the World Bank and United Nations (2010) find that variations in these estimates result from the use of different data and techniques and from the inclusion of different kinds of disasters. This

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[1] In this paper, mitigation refers to the reduction of natural hazard risks, while in other contexts it usually refers to the reduction of greenhouse gas emissions or the enhancement of carbon sinks. Throughout the paper, mitigation is used as a synonym for risk reduction, including adaptation measures in response to changes in the hazard situation. Adaptation in this respect and throughout the paper is understood as adaptation to anticipate changing risks as a result of climate change. As such, adaptation constitutes an integral component of risk mitigation.

poses a considerable obstacle to arriving at reliable, comprehensive and comparable cost figures. Difficulties in establishing comparisons across hazards and sectors are particularly relevant when the resulting cost assessments are to be utilised for decision support and policy development within a risk management framework. To support and guide decision makers in natural hazards management, risk mitigation and adaptation planning for climate change, therefore, it is vital as a first step to synthesise current cost assessment methods and identify current best practices.

Existing overviews of cost assessment methods generally do not address different hazards but often focus on just one particular hazard (e.g. Fuchs and McAlpin, 2005; Merz et al., 2010). In addition, they often look at a specific cost type only (e.g. Papathoma-Köhle et al., 2011). Several such overviews of cost assessment methods exist for floods (e.g. Penning-Rowsell and Fordham, 1994; Smith, 1994; Meyer and Messner, 2005; Messner et al., 2007; Merz et al., 2010). These overviews also consider (at least to some degree) cost assessment approaches for storm surges, as these are similar in many respects to the ones for floods. However, only a few studies provide an overview specifically for coastal hazards (e.g. Costanza and Farley, 2007; Bernatchez et al., 2011, Ciavola et al., 2011). An overview of existing cost assessments for droughts is given, among others, in Wilhite (2000) and Kallis (2008). In relation to Alpine hazards, overviews of existing approaches are given, for example, in Fuchs et al. (2007a), Rheinberger et al. (2009) and Papathoma-Köhle et al. (2011).

## 1.2   Approach and objective of this paper

This paper aims to synthesise current knowledge about cost assessment methods for various hazards and cost types and thus to identify cross-hazard opportunities for learning. It is based on research carried out in the EU project "Costs of Natural Hazards" (CONHAZ) which ran from February 2010 to January 2012. The project adopted a comprehensive approach, considering natural hazards ranging from droughts, floods, storms and coastal hazards to Alpine hazards. At the same time it looked at different sectors such as housing, industry, transport, agriculture, the environment and human health.

In addition, different cost types were considered in the project. Terminology relating to cost types sometimes differs in the literature and among hazard communities (see e.g. Parker et al., 1987; Smith and Ward, 1998; H. John Heinz III Center, 2000; Wilhite, 2000; Thieken et al., 2010). For this reason, a working terminology for cost categories was developed within the CONHAZ project, which takes these different definitions into account. It is largely based on the classification of direct/indirect and tangible/intangible costs, introduced in relation to flood damages by Parker et al. in 1987. However, a novelty within the CONHAZ project was to explicitly include risk mitigation costs as well, and to consider

business interruption costs as a separate sub-category. This results in five cost categories, namely: 1. direct costs, 2. business interruption costs, 3. indirect costs, 4. intangible costs, and 5. risk mitigation costs (see also Fig. 1). The main rational behind distinguishing these five cost categories was that they are likely to require different cost assessment methods. These cost categories are defined as follows:

1. *Direct costs* are damages to property due to direct physical contact with the hazard, i.e. the physical destruction of buildings, inventories, stocks, infrastructure or other assets at risk (Smith and Ward, 1998). The related losses are therefore related predominantly to the assets' susceptibility to the hazard characteristics.

2. *Business interruption costs* occur in areas directly affected by the hazard. Business interruptions take place, for example, if people are not able to carry out their work because their workplace is either destroyed or not accessible due to a hazard. They also occur if industrial or agricultural production is reduced due to water scarcity. In the literature, such losses are sometimes referred to as *direct damages*, as they occur due to the immediate impact of the hazard (see e.g. Wilhite et al., 2007; Kok et al., 2004). They are often also referred to as *primary indirect damages* because the losses do not result from physical damage to property but from the interruption of economic processes (e.g. Smith and Ward, 1998). However, the methods to evaluate losses due to business interruption are quite different from those used for direct or indirect damages. For this reason, and in order to avoid terminological misunderstandings, "business interruption costs" is used as a separate cost category for the purpose of this article.

3. *Indirect costs* are losses induced by either direct damages or business interruption costs (Przyluski and Hallegatte, 2011). They can occur inside or outside of the hazard area and often with a time lag. These losses include, for example, induced production losses of suppliers and customers of companies directly affected by the hazard.

4. *Intangible costs* refer to damages to goods and services which are not measurable (or at least not easily measurable) in monetary terms because they are not traded on a market. Hence, they are also referred to as non-market values or costs (Smith and Ward, 1998). This contrasts to tangible costs, which imply an existing market for tangible assets or the goods and services derived thereof; thus tangible costs are easily expressed in monetary terms. Intangible effects include, for instance, environmental impacts, health impacts and impacts on cultural heritage.

5. *Risk mitigation costs*, i.e. risk reduction, can be regarded as part of the total cost of natural hazards and are thus considered an essential cost category (Bouwer et al., 2011). The costs of risk mitigation can also be classified according to the cost categories introduced above, i.e. direct costs, indirect costs and intangible costs. The direct costs of risk mitigation refer to any costs attributed to research and design, the set-up, operation and maintenance of infrastructure, or other measures for the purposes of mitigating (or adapting to) natural hazards. The indirect costs of risk mitigation relate to any secondary costs (externalities) occurring in economic activities/sectors (or localities) that are not directly linked to such infrastructure investment. The intangible costs refer to any non-market health or environmental impacts of risk mitigation measures, such as environmental damage due to the development of mitigative infrastructure or a change in agricultural practices.
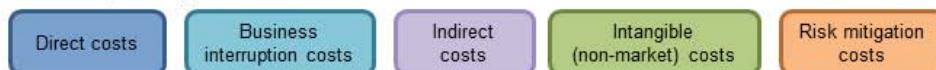
As this last example shows and Fig. 1 illustrates, this cost categorisation includes some overlaps. For example, intangible costs can be direct (e.g. injuries) or indirect damage (e.g. social disruption), or induced by risk mitigation investments (e.g. wetland degradation induced by the construction of dikes). In this article we deal with these overlaps in the following way. The tangible cost categories are discussed in Sect. 2.1 (direct costs), 2.2 (business interruption costs), 2.3 (indirect costs) and 2.5 (all tangible risk mitigation costs), while all intangible categories are presented together in Sect. 2.4 as they require similar valuation techniques.

A review of existing methods for cost assessment was carried out for each natural hazard (floods, droughts, coastal hazards and Alpine hazards) and cost category (direct costs, business interruption costs, indirect costs, intangible costs and risk mitigation costs) considered. This was done based on literature reviews, four expert workshops (one in each hazard community), and a final conference to synthesize findings. In each expert workshop, preliminary results of the reviews were presented to and discussed with 20–30 experts and practitioners from the relevant hazard community. The main purpose of these workshops was to ensure that the reviews cover all relevant methods but also to identify best practices, as well as knowledge gaps. The final synthesis conference then brought together around 60 experts and practitioners from all four hazard communities. This resulted in a joint discussion of methods and knowledge gaps, along with a prioritisation of future research needs.

The results of these reviews are presented in four reports for each different cost type, i.e. for direct costs and costs due to business interruption (Bubeck and Kreibich, 2011), for indirect costs (Przyluski and Hallegatte, 2011), for costs due to intangible, non-market effects (Markantonis et al., 2011), and for costs of risk mitigation (Bouwer et al., 2011). Four other reports present the results for the different hazard types, i.e. droughts (Logar and van den Bergh, 2011), floods (Green et al., 2011), coastal hazards (Lequeux and Ciavola, 2011) and Alpine hazards (Pfurtscheller et al., 2011).

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**Fig. 1.** Cost categorisation applied in this article with examples (adapted from and extended based on Penning-Rowsell et al., 2003; Smith and Ward, 1998).

The objective of this paper is to synthesize the overall findings and conclusions based on these reviews. The specific objectives are 1) to provide a concise summary of state of the art methods for cost assessment for different cost types and hazards and 2) to identify knowledge gaps and the most important research needs. The remainder of this paper is organised as follows. Section 2 presents the main findings concerning current best practices, based on the literature review and expert workshops. Section 3 describes the overall knowledge gaps. By way of a conclusion, key recommendations for practice and further research are provided in Sect. 4.

## 2  State of the art of cost assessment for natural hazards – an overview

In this section, we examine each of the five cost types. For each cost category, we first review the main methods for cost estimates. We then present hazard-specific findings in the latter part of each subsection.

### 2.1  Direct costs

Direct tangible costs, such as the destruction of houses and infrastructure, are among the most visible impacts of natural hazards. They are regarded as a good indicator for the severity of an event. Table 1 presents an overview of methods for estimating direct costs, including examples.

The most frequently applied approach for assessing the direct costs for all the hazards considered is the use of susceptibility functions (or damage functions). What all susceptibility functions have in common is that they describe the relation between one or more hazard parameters, with a resulting monetary damage for a certain type or use of object at risk (Smith, 1981; Parker et al., 1987; Wind et al., 1999; BUWAL, 1999; Keiler et al., 2006; Fuchs et al., 2007b; Corti et al., 2009; Totschnig et al., 2011; Holub et al., 2012). Hazard parameters include, for example, avalanche pressure, water depth or drought-induced soil subsidence. In addition to these hazard parameters, some damage functions also take into account resistance parameters, such as differences in building structures or the standard of risk mitigation measures undertaken (e.g. BUWAL, 1999; Keiler et al., 2005, 2006; BAFU, 2010).

**Table 1.** Direct costs: methods, applications and examples.

| General method | Specific method | Application and/or examples |
| --- | --- | --- |
| Susceptibility function | Single-parameter models (based on single hazard impact parameter) | Floods: Model of ICPR (2001); Model of MURL (2000), adopted by Glade (2003); Model of Hydrotec (Emschergenossenschaft and Hydrotec 2004) Coastal Hazards: Reese et al. (2003) Droughts: Corti et al. (2009) Alpine hazards: Fuchs et al. (2007), Huttenlau (2010), Totschnig et al. (2011) |
| | Multi-parameter models (based on several hazard impact and/or resistance parameters) | Floods: HAZUS-MH (FEMA, 2011; Scawthorn et al., 2006); FLEMOps and FLEMOcs models (Apel et al., 2009; Elmer et al., 2010a; Kreibich et al., 2010; Thieken et al., 2008); Model of Multicoloured Manual (Penning-Rowsell et al., 2003); HIS-SSM (Kok et al., 2004); Model of Maiwald and Schwarz (2010) Coastal hazards: FEMA (2011), HIS-SSM (Kok et al., 2004), Nadal et al. (2010) Alpine hazards: BUWAL (1999), Keiler et al. (2006), Holub et al. (2012) |
| Market valuation techniques | Market price method | Drought: Grafton and Ward (2008) |
| Integrated Assessment Analysis | Biophysical-Agroeconomic Models | Droughts: Holden and Shiferaw (2004), Fischer et al. (2005) |
| | Hydrological-Economic Models | Droughts: Booker et al. (2005), Ward et al. (2006), Grossmann et al. (2011) |
| Computable General Equilibrium Analysis | Computable General Equilibrium Models | Droughts: Horridge et al. (2005) |

Hazard-specific findings include the following:

– Susceptibility functions, in particular depth-damage functions, have a particularly long tradition in the context of flood damage evaluation (e.g. Penning-Rowsell and Chatterton, 1977; Parker et al., 1987; Klaus et al., 1994; IWK, 1999). Over the years a number of multi-parameter models have also been developed, such as those by Nicholas et al. (2001), Zhai et al. (2005), Thieken et al. (2008) and Kreibich et al. (2010). Studies have also shown that the application of multivariate models improve the reliability of flood damage modeling (Apel et al., 2009; Wünsch et al., 2009; Elmer et al., 2010a; Seifert et al., 2010).

– Depth-damage functions have been developed for coastal flooding as well (e.g. Klaus and Schmidtke, 1990; Reese et al., 2003; Kok et al., 2004; Sterr et al., 2005; Nadal et al., 2010).

– Susceptibility functions have also been developed for different Alpine hazards, including for flash floods

(e.g., Holub and Fuchs, 2009; Bründl, 2009; Huttenlau, 2010), debris and mud flows (Fuchs et al., 2007b; Lo et al., 2012), landslides (BUWAL, 1999; Glade, 2003), rock fall (BUWAL, 1999; Huttenlau and Brandstötter-Ortner, 2011) and avalanches (Wilhelm, 1997; BUWAL, 1999; Fuchs et al., 2004; Fuchs and Bründl, 2005; Hilker et al., 2009).

– While the diversity of methods applied for droughts is generally greater, damage functions have also been applied to assess direct drought costs (e.g. Corti et al., 2009, 2011). Moreover, the review by Logar and van den Bergh (2013) concludes that market valuation techniques (i.e. market prices, production function, avoided costs, replacement or repair costs) are the most suitable methods for assessing direct tangible costs of droughts. They have the advantage of being easy to apply, covering any economic sector, and delivering fairly precise estimations. Computable General Equilibrium (CGE) analysis and Input Output analysis are sometimes used to estimate direct costs together with indirect costs (e.g. Horridge et al., 2005), but they require

greater effort in their application. Combined biophysical and agro-economic models integrate crop models with the economic assessment and are thus specifically focused on agriculture (Kulshreshtha and Klein, 1989; Rosenberg, 1993; Holden and Shiferaw, 2004; and Fischer et al., 2005). Hydrological-economic models link the economic assessment to a hydrological model (see e.g. Booker, 1995; Booker et al., 2005; and Ward et al., 2006). Ricardian hedonic price modeling, as in Easterling and Mendelsohn (2000), links variations in land values across space with variations in climate.

## 2.2  Business interruption costs

Three main approaches are applied to assess the costs of natural hazards due to business interruption, namely:

1. applying sector-specific reference values, e.g. for loss of added value, wage losses or relocation expenses per unit affected;

2. comparisons of production output between hazard and non-hazard years; and

3. approaches that calculate production losses using a fixed share of direct damages (see Table 2).

The latter two approaches involve more uncertainties than the first and are therefore useful only for rapid appraisals (e.g. for emergency planning and budgeting). The first approach is considered more comprehensive. Overall, however, these types of losses are usually assessed in practice using rather simplistic methods. The approaches used in the various hazard communities are the following:

– For riverine and coastal flooding, Bubeck and Kreibich (2011) and Green et al. (2011) consider the following approaches to be the best current practices: (1) applying sector-specific reference values, e.g. loss of added value per employee and day (e.g. MURL, 2000), or (2) model approaches for traffic (Department for Transport, 2009) or agriculture (Hess and Morris, 1986). For more rapid cost appraisals, a fixed share of direct damage estimates is often used in practice. Examples are the Australian Anuflood model (NR&M, 2002) and the Rapid Appraisal Method (NRE, 2000). Initial empirical findings support this simplified approach in principle (Kreibich et al., 2010).

– For droughts, the methods most often used are those which evaluate business interruption losses ex post (Benson and Clay, 1998; COPA-COGECA, 2003; Rijkswaterstaat, 2004; Fink et al., 2004; Martin-Ortega et al., 2012). This means that they compare production output or prices between drought and non-drought years.

– A similar approach is used for Alpine hazards to estimate the losses in the tourism industry due to avalanches (Nöthiger, 2003). As in the case of floods, loss of added value approaches are also used, for instance, to estimate the amount of income in the tourism sector forgone per person per day (e.g. Laternser, 2000; SLF, 2000; BML-FUW, 2008a, b).

## 2.3  Indirect costs

The methods used to assess indirect costs of natural hazards are presented in Table 3.

Methods include firm- or household-level surveys relating to past events (e.g. Kroll et al., 1991; Tierney, 1997; McCarty and Smith, 2005) (see event analysis in Table 3), and more frequently economic models, including:

1. econometric models at the local (e.g. Strobl, 2011) or the national level (Albala-Bertrand, 1993; Skidmore and Toya; 2002; Noy and Nualsri 2007);

2. Input Output models at the regional or national level (e.g., Gordon et al., 1998; Okuyama et al., 2004; Hallegatte, 2008; Pérez y Pérez and Barreiro-Hurlé, 2009; Martin-Ortega et al., 2012);

3. CGE models at the regional or national level (e.g., Rose et al., 1997; 2007; Islam, 2003; Rose and Liao, 2005; Tsuchiya et al., 2007; Berrittella et al., 2007; Boyd and Ibarrarán, 2009; Pauw et al., 2010; Wittwer and Griffith, 2010);

4. intermediary models between CGE models and Input Output models (e.g. Hallegatte, 2008).

Other less frequent model-based approaches used to estimate indirect costs consider the impact of natural disasters on public finances (Mechler et al., 2006) or else apply idealized models (Hallegatte and Dumas, 2008; Hallegatte and Ghil, 2008).

The method of collecting data on past events, e.g. based on firm- or household-level surveys, considers a single event in one location. Econometric approaches, by contrast, rely on several events to derive the main explanatory factors for estimating the costs of future events as well. Input Output models estimate the consequences of a specific impact on one or more economic sectors on other sectors of the economy. This is achieved by applying fixed input-output coefficients, which describe relationships between different economic sectors. Such models assume that there is no technological change and no substitution between production inputs. As a result, they may generate overly high estimates of economic losses due to natural hazards. CGE models allow for more flexibility and substitution at different levels, driven by markets and price changes. They may therefore result in lower estimates than Input Output models. However,

**Table 2.** Business interruption costs: methods, applications and examples.

| General method | Specific method | Application and/or examples |
| --- | --- | --- |
| Sector specific reference values or models | Loss of value added | MURL (2000), Laternser (2000), SLF (2000), BMLFUW (2008a, b) |
| | Sector specific models | Department for Transport (2009) |
| Event analysis | Comparison hazard and non-hazard time periods based on reported cost figures | Benson and Clay (1998), COPA-COGECA (2003), Fink et al. (2004), Martin-Ortega et al. (2012), Rijkswaterstaat (2004), Nöthiger (2003) |
| Share of direct damage | Fixed share of direct damage estimates | ANUFLOOD (NR&M, 2002), RAM (NRE, 2000) |

CGE models are also more difficult to apply than Input Output models and have a major shortcoming in that they assume that markets will function perfectly (even in post-disaster situations). Intermediate models are either Input Output models with flexibility, as in Hallegatte (2008), or CGE models with reduced substitution elasticity, as in Rose et al. (2007).

Another approach uses the impact of natural disasters on public finances. Its aim is to assess indirect costs in terms of the government's capacity to cope with large amounts of expenditure due to natural disasters and their subsequent ability to deliver basic services in the aftermath. This approach implicitly considers the impacts on public finances and their capacity to overcome these challenges as a proxy for indirect costs. One example of this is the IIASA CATSIM model developed by Mechler et al. (2006) and applied to Honduras.

Another approach used to assess indirect costs is to develop idealized models aimed at emphasizing one or more particular relation(s) or mechanism(s) at play in the economic system after a natural hazard. These include interactions between hazard impacts and technical change (Hallegatte and Dumas, 2008) or business cycles (Hallegatte and Ghil, 2008). Even though their main aim is not to assess the costs of extreme events directly, nonetheless they help to identify important mechanisms and to investigate their role.

The following are some examples of applications in the different hazard communities:

– For *droughts*, CGE models (e.g. Islam, 2003; Horridge et al., 2005; Berrittella et al., 2007; Boyd and Ibarrarán, 2009; Pauw et al., 2010; and Wittwer and Griffith, 2010) and Input Output models (e.g. Martin-Ortega et al., 2012; Pérez y Pérez and Barreiro-Hurlé, 2009) are often applied in practice. Logar and van den Bergh (2013) consider both to be the most complete methods

to assess the indirect costs of droughts because they take all economic sectors into account.

– A regional Input Output model has also been applied for *coastal hazards* in the case of Hurricane Katrina (Hallegatte, 2008).

– For *riverine flooding*, econometric approaches, CGE and Input Output models dominate (Green et al., 2011; Przyluski and Hallegatte, 2011).

– For *Alpine hazards*, just a few studies exist which consider indirect effects, based on an analysis of past events (Nöthiger, 2003; Kletzan et al., 2004).

Green et al. (2011) and Pfurtscheller et al. (2011) suggest that the usefulness of CGE and Input Output models for decision support on smaller scales in particular may be debatable, as they fail to meet stakeholders' needs. For instance, most stakeholders are interested in assessing the indirect impact of various types of events, both large and small, at micro (cities) or meso (catchment) scale, with or without risk mitigation measures. However, most of the methods discussed can only assess the impacts of an extreme event on the national or sometimes regional scale. Furthermore, Green et al. (2011) regard the potential transfer of these methods to practitioners as being quite unrealistic. The reasons for this are that the models require a high degree of skill to run and entail complex mechanisms and uncertainties. Alternative approaches for assessing the indirect costs at a local scale are currently still lacking (Green et al., 2011; Pfurtscheller et al., 2011).

**Table 3.** Indirect costs: methods, applications and examples.

| General method | Specific method | Application and/or examples |
|---|---|---|
| Event analysis | Surveys at firm level | Boarnet (1998), Kroll et al. (1991), Tierney (1997) |
| | Surveys at the household level | McCarty and Smith (2005) |
| Econometric approaches | Gross regional product effect assessment | Noy and Vu (2009), Strobl (2011) |
| | National Gross domestic product effect assessment | Albala-Bertrand (1993), Cavallo and Noy (2009), Hochrainer (2009), Jaramillo (2009), Noy (2009), Loayza et al. (2009), Noy and Nualsri (2007), Raddatz (2009), Skidmore and Toya (2002) |
| Input-Output Analysis | Input-Output Models | Hallegatte (2008), HAZUS-E (see also McCarty and Smith, 2005), Haimes et al. (2005), Okuyama et al. (2004), Rose and Liao (2005), Rose and Miernyk (1989) |
| Computable General Equilibrium Analysis | Computable General Equilibrium Models | Berrittella et al. (2007), Boyd and Ibarrarán (2009), Horridge et al. (2005), Pauw et al. (2010), Rose et al. (2007), Tsuchiya et al. (2007), Wittwer and Griffith (2010) |
| Intermediate models | Hybrid Input-Output/ Computable General Equilibrium Models | Hallegatte (2008), Rose et al. (2007) |
| Public Finance Analysis | Analysis of the impact on public finance | Mechler et al. (2006) |
| Idealized Models | Modeling interactions of hazard impacts with technical change or business cycles | Hallegatte and Dumas (2008), Hallegatte and Ghil (2008) |

## 2.4  Intangible (non-market) costs

Intangible (non-market) costs do not necessarily have to be expressed in monetary terms in order to be included in decision support frameworks. In a Multicriteria Analysis framework, for example, they can be included as non-monetary decision criteria or, in a Cost-Effectiveness Analysis framework, as a non-monetary target measure. However, to be included in a Cost-Benefit Analysis framework, intangible costs have to be expressed in monetary terms.

Methods for estimating the monetary value of intangible effects of natural hazards consider both use and non-use values that individuals derive from environmental or health goods and services. While use values relate to the direct, indirect or even optional use, non-use values relate to the value individuals derive from just knowing that a certain environmental good exists or that it is being preserved for future generations. Different valuation methods are proposed according to each type of (non-)use value. These methods can be categorised (as presented in Table 4) into:

1. revealed preference and

2. stated preference valuation methods.

The accuracy and effectiveness of these valuation methods depend on the availability and quality of the data (including the quality of the survey design), the available resources and the decision made in each case on the most appropriate method for estimating the intangible effects.

Revealed preference methods have the advantage of estimating the value of a particular good based on actual market behaviour, i.e. ex post. Information derived from observed behaviour is used to derive an individual's willingness to pay for an environmental improvement or for avoiding environmental deterioration. The main revealed preference methods are the following (cf. Pearce and Turner, 1990; Hanley and Spash, 1993; Birol et al., 2006):

- Travel Cost method: recreational or environmental sites are valued by analysing observed travel time and expenditure of visitors (see e.g. Hartje et al., 2001).

- Hedonic Pricing method: the value of environmental characteristics is estimated based on actual market prices, in particular from the housing market (see e.g. Hamilton, 2007).

- Cost of Illness approach: costs of health impacts are estimated based on medical costs and lost wages due to illness (see e.g. DEFRA, 2007).

- Replacement Cost method: the value of an ecosystem good or service is estimated based on the costs of replacing that good or service (see e.g. Leschine et al., 1997).

- Production Function approach: the value of an environmental good which is used to produce a market good is estimated based on the producer´s production function (Birol et al., 2006).

In contrast, stated preference methods create a hypothetical or contingent market in a survey. They use willingness to pay, or willingness to accept compensation for relinquishing an environmental deterioration or to forego an environmental improvement. Important stated preferences approaches for estimating the environmental and health goods or services are the following (cf. Pearce and Turner, 1990; Hanley and Spash, 1993; Birol et al., 2006):

- Contingent Valuation (CV) method: in order to valuate non-market goods, people are asked in surveys about their willingness to pay to avoid a given decrement of this particular non-market good, or about their willingness to accept its deterioration by receiving a certain amount of compensation (see e.g. Leiter and Pruckner, 2007).

- Choice Modelling (CM) method: willingness to pay is elicited by choice experiments in which people can choose between different bundles of goods with varying characteristics. These can either be market or non-market goods (see e.g. Olschewski et al., 2011).

- The Life Satisfaction Analysis: welfare estimations of public goods (health, environment) are estimated based on life satisfaction surveys (Carroll et al., 2009).

Furthermore, Benefit or Value Transfer methods can be used to transfer the results of previously applied valuation methods to a new case study in order to estimate the intangible costs (e.g. Martin-Ortega et al., 2012).

Among the stated preference methods, CV has been the most commonly used method in valuating non-market goods and services for a long time. It has also been applied in the assessment of the intangible costs of natural hazards (see Turner et al., 1993; Daun and Clark, 2000; DEFRA, 2004; Leiter and Pruckner, 2007). CM has become more popular in recent years. Both CV and CM can estimate economic values for any environmental resource. Their advantage over other methods is that they can estimate non-use values as well as use values. CM, however, additionally makes it possible to estimate the implicit values of its attributes, their implied ranking and the value of changing more than one attribute at a time (Hanley et al., 1998; Bateman et al., 2003).

Applications in the different hazard communities are the following:

- Possibly, the most applications have been carried out in the context of floods (see e.g. Daun and Clark, 2000; DEFRA, 2004). However, Green et al. (2011) highlight the importance of first learning more about the impacts of floods on people and the environment rather than trying to monetize them right away.

- The particular characteristics of droughts, such as their long duration and much slower onset than other natural hazards, make it more difficult to estimate their intangible costs (Markantonis et al., 2011). So far, CV (e.g. Bakarat and Chamberlin, Inc., 1994; Howe et al., 1994; Griffin and Mjelde, 2000; Koss and Khawaja, 2001; Pattanayak and Kramer, 2001a), CM (Hensher et al., 2005; 2006), Life Satisfaction Analysis (Carroll et al., 2009) and Benefit Transfer methods (Martin-Ortega et al., 2012) have been used to assess them.

- Only a few attempts have been made in practice to estimate the intangible costs of coastal hazards. These include Hedonic Pricing (see e.g. Hamilton, 2007), Travel Cost methods (see e.g. Hartje et al., 2001) and CV (see e.g. Turner et al., 1993).

- In the field of Alpine hazards, the CV method has been used in a few studies to assess the intangible costs (Leiter and Pruckner, 2007; Rheinberger, 2009).

**Table 4.** Intangible effects: methods, applications and examples.

| General method | Specific method | Application and/or examples |
|---|---|---|
| Revealed preferences methods | Travel Cost method | Hartje et al. (2001) |
| | Hedonic Pricing method | Hamilton. (2007), Chao et al. (1998), Cavailhes et al. (2009) |
| | Cost of Illness approach | DEFRA (2007) |
| | Replacement Cost method | Leschine et al. (1997) |
| | Production Function Approach | n.a. |
| Stated preferences methods | Contingent Valuation method | Birol et al. (2006), Daun and Clark (2000), DEFRA (2004), Leiter and Pruckner (2007), Pattanayak and Kramer (2001b), Turner et al. (1993), Zhai and Ikeda (2006), Zhongmin et al. (2003) |
| | Choice Modelling method | Brouwer and Schaafsma (2009), Daun and Clark (2000), Hensher et al. (2006), Olschewski et al. (2011) |
| | Life Satisfaction Analysis | Carroll et al. (2009) |
| Benefit or Value Transfer methods | | Martin-Ortega et al. (2012) |

Revealed and stated preferences methods are also applied when assessing intangible costs caused by risk mitigation measures. These include the Hedonic Pricing method, applied for aesthetic costs arising from land use planning measures (Hamilton, 2007) and land fragmentation and habitat loss due to infrastructure investments (Cavailhes et al., 2009). In addition, CV and CM have been applied to value the intangible costs of infrastructure measures (Van der Heide et al., 2008), hazard modification measures (Brouwer and Schaafsma, 2009) and emergency response and evacuation (Zhai and Ikeda, 2006).

## 2.5 Risk mitigation costs

Measures to mitigate risk identified in the CONHAZ project included the following categories (Bouwer et al., 2011, 2013):

1. risk management planning and adaptation plans

2. hazard modification

3. infrastructure

4. mitigation measures sensu stricto

5. communication

6. monitoring and early warning

7. emergency response and evacuation

8. financial incentives

9. risk transfer

Table 5 presents the main methods to assess the direct costs attributed to risk mitigation.

Cost assessment for risk mitigation measures focuses almost exclusively on estimating direct costs, including research and design, and set-up costs. The reason is that these costs are most easily quantifiable. The direct costs of mitigation are based on readily available market prices that relate to either the actual cost of implementation (see Fuchs et al., 2007a; Pfurtscheller and Schwarze, 2010; Stoffel, 2005; Kind, 2013; Kreibich et al., 2011; European Commission, 2008; Von Ungern-Sternberg, 2004; Schwarze et al., 2011)

**Table 5.** Risk mitigation costs: methods, applications and examples.

| General method | Specific method | Application and/or examples |
| --- | --- | --- |
| Market price | Cost of Implementation | Fuchs et al. (2007), Morton et al. (2005), Pfurtscheller and Schwarze (2010) (emergency response and evacuation); Pattanayak and Kramer (2001a, b), Stoffel (2005) (hazard modification); Fischer et al. (2005), Kind (2013) (infrastructure); Kreibich et al. (2011) (mitigation measures – sensu stricto); European Commission (2008), Hallegatte (2012) (monitoring and early warning systems); Fisher et al. (1995), Woo (1994), Von Ungern-Sternberg (2004) (financial incentives); Michelsen and Young (2003), Schwarze et al. (2011) (risk transfer) |
| | Income Loss from Disruption of Economic Activity | Rogers and Tsirkunov (2010) (monitoring and early warning systems) |

or income loss due to the disruption of economic activity (Rogers and Tsirkunov, 2010) (see Table 5). The focus is often on direct investments in "hard" risk mitigation measures, i.e. the categories infrastructure and mitigation measures (sensu stricto). Thus, with a few exceptions (see e.g. Wegmann et al., 2007), comprehensive and comparable overviews of total mitigation costs, whether at regional or national level, are rarely available.

Although different approaches exist for estimating indirect and intangible costs of risk mitigation measures (see Sects. 2.3 and 2.4), less emphasis is given to these costs in studies that focus on the cost assessment of these measures. Such costs can be important and their exclusion can lead to incomplete and biased estimates of the overall costs of risk reduction. Any reliable Cost-Benefit Analysis of infrastructure investment (for mitigation of or adaptation to natural hazards) requires an accurate estimation of all costs associated with the inception and implementation of the project (i.e. during the asset's entire life cycle). The Whole Life Cycle Costing approach (see e.g. Langdon, 2007; Viavattene and Faulkner, 2012) attempts to provide such a systematic consideration of all present and future costs linked to risk mitigation investment (and assets more broadly).

– For riverine and coastal flooding, a fairly long tradition of evaluating risk mitigation measures within Cost-Benefit Analysis frameworks exists in Europe (see e.g. MAFF, 1999). However, as for natural hazards in general, often only structural and technical risk mitigation measures are considered. There also tends to be a heavy emphasis on implementation costs. The extent of operation and maintenance costs is not properly included, as these costs are often estimated by simply assessing them as percentages of construction costs (Bouwer et al., 2011).

– For droughts, the few studies that try to assess the costs of mitigation measures include Michelsen and Young (1993), Woo (1994), Fisher et al. (1995), Pattanayak and Kramer 2001a, b), Morton et al. (2005), and Grafton and Ward (2008).

– For Alpine hazards, the costs of risk mitigation measures – not only structural measures but also monitoring and early warning activities – has received considerable attention (Holub and Fuchs, 2009; Holub et al., 2012). There have also been some initial attempts to assess the costs of emergency response and evacuation measures (Fuchs et al., 2007a; Pfurtscheller and Schwarze, 2010). One of the most comprehensive studies on the

costs of risk reduction was conducted by Wegmann et al. (2007) for Switzerland, revealing the percentage of GDP spent on risk mitigation (including insurance premiums). However, such results are only comparable to a limited extent with other regions or nations due to a lack of data and non-standardized methodologies.

# 3 Knowledge gaps

Following the foregoing state-of-the-art overview of cost assessment methods of natural hazards, this section focuses on the remaining knowledge gaps. Hazard-specific knowledge gaps were identified as part of the different reviews described in Sect. 1 and discussed by experts in the corresponding workshops. Overall knowledge gaps were subsequently identified, discussed and prioritized by researchers and practitioners at the synthesis conference. The most important knowledge gaps are presented in the following subsections. These include (1) overarching problems relating to the incompleteness and uncertainty of cost assessments. The reasons for these uncertainties are addressed in separate subsections, namely, (2) the lack of data sources, and (3) shortcomings of existing methods. Further important knowledge gaps relate to (4) the future dynamics of risk in cost assessments, (5) the distribution of costs within society, and (6) using cost assessments for decision support.

## 3.1 Comprehensiveness and uncertainty

The review of existing methods and practices relating to cost assessments for natural hazards revealed that there is a strong focus on the direct costs of natural hazards. By contrast, business interruption costs, intangible (non-market) costs such as health and environmental effects, and especially indirect costs are often underestimated or even neglected entirely (cf. Handmer, 2003; Meyer et al., 2009; Lequeux and Ciavola, 2011; Pfurtscheller et al., 2011). This may lead to incomplete cost estimates and, hence, risk management decisions which are biased towards the mitigation of direct costs.

Additionally, major uncertainties still remain in all parts of cost assessments. Note that there are different understandings of "uncertainty" in different disciplines. See, for example, Knight (1921) for the classical differentiation between risk and uncertainty in economics, or Gross (2007) for a review of connotations of different types of the "unknown" in sociology. In this article, we refer mainly to "epistemic uncertainty" as used by Merz and Thieken (2005, 2009): whereas natural (or aleatory) uncertainty stems from the variability of the underlying stochastic process, epistemic uncertainty results from incomplete knowledge about the process under study, e.g. from aggregated or absent input data or modeling uncertainties. Although considerable improvements have been made over the last few decades, such epistemic uncertainties are still considerable and are also difficult to assess.

They are related to, among other things, inadequate or aggregated data sources (cf. Sect. 3.2), a lack of knowledge about the processes leading to damage and the resulting lack of appropriate models (cf. Sect. 3.3, Handmer, 2003; Merz and Thieken, 2009; Bubeck and Kreibich, 2011; Pfurtscheller et al., 2011; Przyluski and Hallegatte, 2011). As a consequence, the aims should be to identify and reduce the main sources of uncertainty and to document any remaining uncertainties in the results section of cost assessments.

## 3.2 Lack of data sources

As outlined above, one of the main sources of uncertainty in cost assessments for natural hazards is the lack of sufficient, detailed, comparable and reliable data (Handmer, 2003). Improvements can be made with regard to (1) the collection of ex post event data and (2) the availability of secondary input data sources for ex ante cost estimations.

First, ex post event data on damage or loss is needed to better understand the processes that give rise to damage, to identify the most important factors influencing damage, and to develop, calibrate and/or validate models. This applies to direct damage data, data on business interruption, indirect costs, health and environmental effects, but also the specific costs of risk mitigation measures (cf. Bubeck and Kreibich, 2011; Bouwer et al., 2011; Logar and van den Bergh, 2011). Different databases may include different biases (Gall et al., 2009). For example, small events are lacking in global databases as opposed to national databases. Furthermore, databases are sometimes inconsistent as they show different figures, for example, for the numbers of fatalities and disaster costs (see Pfurtscheller et al., 2011 for some examples regarding Alpine hazards). Although several data collection activities have been conducted in different countries and for different cost types (e.g. EM-DAT, Munich Re, Swiss Re Sigma, StoreMe, see also Barredo, 2009), there is still a lack of data that link object-specific damage costs with event/impact parameters and object characteristics. One case where this has been done is the HOWAS 21 database (Thieken et al., 2009), which collects, documents and integrates flood damage data for individual properties (see HOWAS 21, 2012). The items included here were derived from an expert survey aimed at reaching a consensus on information items at the object level. Such a consensus is of utmost importance for the development of micro-scale damage models in different sectors (see Elmer et al., 2010b; Thieken et al., 2010).

Second, there is often a lack of sufficient input data for ex ante cost assessment models. For example, models for direct cost assessments require high spatial resolution data on land use, type of buildings, asset values of buildings and contents, industrial production and crop yields as input data (Green et al., 2011). Such data are often available only at a highly aggregated level (Messner et al., 2007). Furthermore, the different data sources are often incompatible with each

other in terms of categorisation and/or spatial resolution. For example, detailed and normalized long-term data on housing market values are required for revealed preference approaches (cf. Markantonis et al., 2011). Methods for estimating indirect effects would require data on networks and Input Output relationships between different sectors (cf. Przyluski and Hallegatte, 2011). Such data are often not available at local or regional level. A further drawback is that some of these data sources are often either costly (land use data) or not accessible at a high spatial resolution for reasons of security or privacy protection (e.g. asset value data). Primary data collection, i.e. original surveys, may be an option for closing such data gaps, albeit a costly and time-consuming one.

### 3.3 Shortcomings of existing methods and their application

Another source of uncertainty in cost assessments are shortcomings in existing methods. In the following subsections, these shortcomings are summarized with regard to the different cost categories. One knowledge gap that affects many existing damage models is that they are often not validated. However, such validations are needed in order to determine the accuracy of cost assessments (Bubeck and Kreibich, 2011). Validations such as those described by Kirwan (1997) may ideally use comparisons between predicted damages and observations (absolute validation). However, other ways of assessing the validity of damage models are also possible. These include the use of expert knowledge, comparisons of alternative damage models, and methods for evaluating the process of model construction (second or third order validation, see Kirwan 1997). While a number of absolute validations have been carried out with respect to flood damage modeling (see e.g. Thieken et al., 2008; Apel et al., 2009; Wünsch et al., 2009), very few similar exercises have been conducted for droughts, coastal flooding or Alpine hazards. In addition, many damage models are simply transferred in space and time, i.e. from region to region or from one event to the other. However, it is still an open question as to what extent and under which conditions this is possible. Model validations in different regions and at different points in time, as well as model intercomparison studies, could provide insights into this issue, as demonstrated by Bubeck et al. (2011) and Jongman et al. (2012).

#### 3.3.1 Direct costs and business interruption costs

As mentioned in Sect. 2, susceptibility functions – the most common approach to estimating direct costs – often only refer to single hazard and resistance parameters, such as inundation depth and building type (see e.g. IWK, 1999). This may result in an oversimplification of the processes leading to damage and, hence, to inaccurate cost estimates (see Bubeck and Kreibich, 2011). Recent research has shown that

models which include more parameters outperform simple models (Thieken et al., 2008; Elmer et al., 2010a). Since the contribution of households to damage reduction has gained increasing importance in contemporary integrated risk management strategies (e.g. Bubeck et al., 2012), special attention should be paid to integrate resistance parameters in cost assessments (see e.g. Holub et al., 2012). Information on such resistance parameters provides key insights for risk management, as it enables evaluation and comparison of various structural and non-structural risk mitigation strategies (Bubeck and Kreibich, 2011).

Existing methods often focus on cost assessments for single sectors (cf. Bubeck and Kreibich, 2011; Logar and van den Bergh, 2013). For instance, damage models for floods often concentrate on private housing (residential sector) (see e.g. Elmer et al., 2012), and those for droughts on the agricultural sector (see e.g. Horridge et al., 2005). However, the processes leading to damage may differ significantly according to sector and hazard. Furthermore, the combined effects of coinciding or cascading hazards, such as storms or coastal floods, are usually not reflected in the models (cf. Lequeux and Ciavola, 2011). Recent attempts to close this gap include those in Kappes et al. (2012) and the ongoing research project MATRIX (New Multi-Hazard and Multi-Risk Assessment Methods for Europe, see also MATRIX, 2013).

Furthermore, the role of protection measures and management schemes is often not adequately reflected in the damage models, and yet the failure of existing defence structures can be one of the most influential factors leading to damage (cf. Green et al., 2011; Holub et al., 2012). As an example, PLANALP (2008) recommends that the performance of risk mitigation structures should be tested for the eventuality of overload (see Pfurtscheller et al., 2011).

The assessment of business interruption costs tends to be conducted using rather simplistic models (see also Sect. 2.2).

Although it is widely acknowledged that direct or business disruption costs give rise to indirect costs, so far little attention has been paid in the models to linking the estimation of direct costs with that of indirect costs. As a result, a knowledge gap remains regarding ways of feeding direct cost estimations into methods for indirect cost assessment.

#### 3.3.2 Indirect costs

Although models exist to estimate the indirect costs of natural hazards (cf. Sect. 2; Przyluski and Hallegatte, 2011), there is still little understanding of economic responses to external shocks. Specifically, this relates to how an economic system can respond and adapt during the recovery and reconstruction phase.

Existing models often operate on an aggregated scale, i.e. the total direct impact of a natural hazard is used as an input to CGE models or Input Output models (Pérez y Pérez and Barreiro-Hurlé, 2009). So far, little attention has been paid to the micro scale, that is, to how the impact of a natural

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Nat. Hazards Earth Syst. Sci., 13, 1351–1373, 2013

hazard on individual elements of critical infrastructure or single nodes or hubs in network systems may influence the economic system as a whole. Examples of such critical elements are the electricity supply system, water distribution, transportation, along with critical industries in the supply chain. The links between direct and indirect cost assessment are not yet sufficiently clear to generate such an understanding (cf. Przyluski and Hallegatte, 2011).

Improving these links would also imply a better understanding of interactions between intrinsic economic dynamics (e.g. business cycles) and external shocks (e.g. natural disasters). The co-existence of these two dynamics explains why it is so difficult to "extract" the effect of natural disasters from macroeconomic data series (cf. Przyluski and Hallegatte, 2011). The assumptions underlying Input Output models and CGE models (see Sect. 2.3) suggest that neither of these models is perfectly able to reflect reality. CGE models, furthermore, require considerable effort and expertise. More work on intermediate models (e.g. Rose et al., 2007; Hallegatte, 2008) might overcome at least some of these shortcomings, for example by making Input Output models more flexible and CGE models easier to apply. Such intermediate models also emphasize the importance of critical sectors such as infrastructure, electricity and water. In addition, approaches such as agent-based modelling (Castle and Crooks, 2006) and general systems modelling (Arthur, 2010) may provide greater understanding about the critical issues pertaining to the impacts of a shock on an economic system.

### 3.3.3   Intangible (non-market) costs

As stated before, intangible/non-market costs of natural hazards such as those caused by environmental and health impacts have rarely been included in cost assessments up to now, despite the variety of valuation methods available (cf. Markantonis et al., 2011, 2012; they also provide a more detailed discussion on the advantages and disadvantages of these methods). However, as such costs may constitute a significant part of the overall costs they should be considered in decisions on risk mitigation measures.

Alongside the importance of considering intangible costs by applying available valuation techniques (see Sect. 2.4), a more crucial knowledge gap often lies in the precise description and analysis of the physical processes leading to intangible costs (cf. Markantonis et al., 2011, 2012). The environmental and health impacts of natural hazards are often not properly understood and are therefore not easy to model. For instance, the impacts of natural hazards on mental health have rarely been analysed up to now (see e.g. DEFRA, 2007).

### 3.3.4   Costs of risk mitigation

The costs of risk mitigation measures constitute an essential part of the total costs related to natural hazards. They should therefore be considered in cost assessments, and in partic-

ular in decision-making processes on alternative mitigation options. However, as the review by Bouwer et al. (2011) shows, cost assessments of risk mitigation measures focus almost exclusively on direct costs, especially on investment, research and design costs. Operation and maintenance costs are rarely considered, and the indirect and intangible costs of risk mitigation measures are often ignored.

Furthermore, cost assessments of risk mitigation measures focus mainly on structural measures aimed at hazard prevention, such as dikes and avalanche protection. By contrast, there are comparatively few cost assessment approaches for non-structural measures, such as small-scale risk mitigation actions, monitoring and warning systems, emergency response, land use planning or risk transfer systems (Bouwer et al., 2011; Meyer et al., 2012b). To conduct a comparative evaluation of alternative structural and non-structural risk mitigation options, it would be necessary to obtain reliable cost figures for both (cf. Green et al., 2011).

### 3.4   Future dynamics of risk

Natural hazard risks are essentially dynamic, depending on climate variability as well as on changes in vulnerability patterns (IPCC, 2012). Risks and their associated costs will continue to change in the future due to the dynamics of different risk drivers. Such intrinsic dynamics include changes in the probabilities or intensities of hazards due to climate change on the one hand and socio-economic developments on the other (Elmer et al., 2012; Cammerer et al., 2012; Cammerer and Thieken, 2013). The latter include land use changes, demographic changes and changes in asset values at risk, as well as changes in the susceptibility of such elements at risk and the adaptive capacity of communities (cf. Hufschmidt et al., 2005; Bouwer et al., 2011; Przyluski and Hallegatte, 2011). These dynamics are only rarely reflected in current cost assessment practice. In other words, it is often implicitly assumed that the current risk situation will not change: annual average damages figures are simply extrapolated into the future. Just a few studies to date have attempted to integrate both climate change scenarios and socio-economic change scenarios (see e.g. Fuchs et al., 2005; Elmer et al., 2012; Bouwer, 2013).

### 3.5   Distribution of costs and risk transfer

Besides the total costs of natural hazards, their distribution within a society is an important issue which has received little attention so far (cf. Green et al., 2011). For decision-making purposes, it is important to know who suffers most in the aftermath of natural hazards, who bears the costs of potential risk mitigation options and who benefits from them. Some improvements have already been made in developing risk-mapping approaches that identify affected population groups more precisely in spatial terms (Merz et al., 2007; Fuchs et al., 2009; De Moel et al., 2009; Meyer et al., 2012a).

In addition, however, the lack of financial resources among the people or companies affected may be a critical factor in a society's ability to recover from the shock. Risk transfer systems such as insurance and re-insurance schemes are an important means of distributing such costs within a society in order to make the system as a whole more resilient to such shocks (cf. Fuchs, 2009; Raschky et al., 2009; Przyluski and Hallegatte, 2011; Schwarze et al., 2011). Some evidence has also been provided to show that insurance systems additionally provide an opportunity to include incentives to reduce risks (see e.g. Thieken et al., 2006; Bouwer et al., 2007; Pompe and Rinehart, 2008; Warner et al., 2009; Botzen et al., 2009; Aerts and Botzen, 2011).

## 3.6 Cost assessment as decision support

The previous sections have focused on approaches to cost assessments for natural hazards. As stated at the beginning of this paper, the main objective of such cost assessments is to provide a basis and a support for better decision making and improved risk management (WB and UN, 2010; IPCC, 2012). This section therefore deals with shortcomings and knowledge gaps in decision support approaches.

The traditional framework for an economic assessment of the costs of natural hazards is Cost-Benefit Analysis (see e.g. MAFF, 1999). The main objective is to find the most efficient course of action. All benefits of alternative risk mitigation options are related to their costs in order to identify the course of action with the highest net benefit, compared to a baseline option (Pearce and Smale, 2005; Meyer et al., 2012b). However, as the overview of knowledge gaps in the preceding sections has revealed, the state of the art of cost assessment is still far from delivering comprehensive and precise monetary figures for all the costs entailed by natural hazards. Hence, cost assessments do not yet provide an overall picture of the total costs and benefits of possible risk mitigation measures.

Nevertheless, monetary cost assessments and Cost-Benefit Analyses can provide crucial support for decision makers. Furthermore, many improvements have been made and will probably be made in the future to enhance the comprehensiveness and precision of cost estimates. It should be acknowledged, however, that such cost estimates will always be uncertain and imprecise to some degree (Handmer, 2003; Downton and Pielke, 2005). These uncertainties in cost estimates should be documented to the best possible extent. Ultimately, it is up to the elected decision makers to judge the extent to which these monetary cost figures are useful to them in making better decisions or, indeed, to what extent non-monetary decision criteria should also be considered. In this context, Cost-Benefit Analysis can be a useful tool, but it could be usefully embedded in a wider Multicriteria Analysis framework. This would allow stakeholders and decision makers to decide on the relative importance of the different decision criteria and their related uncertainties (Green et

al., 2011). If decision makers can agree upon a single non-monetary target indicator, even Cost-Effectiveness Analysis can be a helpful economic evaluation tool to achieve a desired target level in a cost-effective manner (Meyer et al., 2012b). The steps and decision rules of each of these decision support methods should be made transparent to the decision makers.

Furthermore, it should be acknowledged that cost assessments are always related to a specific purpose (see also WB and UN, 2010). This means that cost assessments for the insurance industry or for a private company are based on different assumptions than those of cost assessments for a national economy (Smolka, 2006), resulting in diverging cost figures. In addition, costs are always dependent on the baseline scenario, i.e. the course of action to which the costs and benefits of all other options are compared. In consequence, communicating cost figures without mentioning the baseline scenario can lead to misunderstandings.

## 4 Conclusions

This article presents a review of available methods for estimating the costs of natural hazards, including floods, droughts, coastal and Alpine hazards. In addition, the review distinguishes between different cost categories, namely direct costs, business interruption costs, indirect costs, intangible costs and risk mitigation costs. The knowledge gaps (presented in Sect. 3) and related recommendations have been discussed at a synthesis conference involving about 60 experts from science, policy, insurance companies and consultancies from the different hazard communities. Based on these discussion sessions and a final prioritization of topics during the synthesis conference, it was possible to extract the following key issues and recommendations:

- Cost assessments are often incomplete and biased. In order to obtain a complete picture of the costs of natural hazards, not only direct costs but also costs due to business interruption, indirect and intangible/non-market costs as well as the costs of risk mitigation should be considered.

- Although improvements have been made over the last few decades, considerable uncertainties still exist in all parts of cost assessments. In any appraisal it is therefore important to identify the main sources of uncertainty at an early stage and try to reduce or handle them. Any residual uncertainties in cost estimates should be documented and communicated to decision makers.

- One of the main sources of uncertainty in the estimation of the costs of natural hazards is the lack of sufficient, comparable and reliable data. A framework for supporting data collection should be established at the European level, both for object-specific ex post damage

data (event analysis) and risk mitigation costs. Such a framework should ensure sufficiently detailed information and minimum data quality standards to facilitate the development and consistency of European and national databases.

– In general, there is a need for a better understanding of the processes leading to damage so that they can be modeled appropriately. With regard to direct damages, multi-parameter damage models are needed that better capture the variety of damage influencing parameters, including resistance parameters.

– With regard to indirect costs, more research is needed to understand and to model how markets function outside the state of equilibrium and at different scales. This applies particularly to the dynamics of return to equilibrium after a hazardous event, the associated social and institutional interactions and how agent expectations are formed in situations of high uncertainty.

– With regard to intangible costs, further research is needed on the physical impacts of natural hazards on the environment and human health.

– With regard to the costs of risk mitigation, special emphasis should be given to a better estimation of the costs of non-structural measures.

– More research is needed on the impacts of climate and socio-economic change on the future costs of natural hazards and the costs of adaptation to these changes. At the same time, it remains important to determine how such findings can be integrated into cost assessment methods. In this respect, the exchange of knowledge between the natural hazard risk community and the climate change community should be improved.

– There is a need for appropriate tools, guidance and knowledge transfer to support decision makers when integrating cost assessment figures into their decision making process. Such tools or frameworks should communicate and consider uncertainties in cost figures and ensure the transparency of the decision rules.

The review of existing methods and their application in practice additionally showed that sometimes there are already cost assessments available for various hazard communities but that there is a limited exchange of information between them. For example, extensive knowledge is currently available for floods (especially for the estimation of direct costs) and this knowledge has, in turn, been transferred to coastal and Alpine floods. However, there is a need to adapt these approaches, developed specifically for riverine flooding, to the special conditions of coastal or Alpine floods in order to identify differences in processes leading to damage (see e.g. Nadal et al., 2010).

The potential to transfer direct cost assessment approaches to drought, for instance, does exist (see Corti et al., 2009) but can be seen as rather limited. This stems from the specific nature of drought hazards, which are mostly slow onset, long lasting events. At the same time, it seems that for droughts more experience is available on linking methods for direct and indirect cost assessments. In general, methods for assessing direct costs are more hazard specific (i.e. less easy to transfer from one hazard to another) than methods for assessing indirect costs.

Cost assessments for both coastal and Alpine hazards have to deal with multiple and coinciding hazards. While acknowledging the differences between hazard types, there may nonetheless be potential for an exchange of knowledge and information within and between these communities on how to deal with such issues.

In addition to the potential for knowledge exchange across the different research communities, there is a broader need for further knowledge transfer from research to practice. The workshops conducted showed that practitioners are aware of the potential importance of indirect and intangible costs but that they still lack expertise in the relevant methods and tools to assess them (cf. Pfurtscheller et al., 2011).

To sum up, the knowledge gaps identified and recommendations proposed in this paper may contribute towards developing cost assessments that support better risk management and risk reduction in the future. Integrating cost assessments into risk management may support decision makers in their choice of appropriate risk mitigation measures and in prioritising and combining them efficiently. Such an integrated framework may prove most useful if it can be applied by different actors in risk management to achieve their specific aims. It would need to include all relevant cost types, take account of and communicate uncertainties transparently, and consider the dynamics arising from changing risks and socio-economic developments.

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