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REVIEW ARTICLE “ASSESSMENT OF ECONOMIC FLOOD DAMAGE”

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ABSTRACT **Damage assessments of natural hazards sup- ply crucial information to decision support and policy development in the fields of natural hazard management and adaptation planning to climate change. Specifically, the estimation of economic flood damage is gaining greater importance as flood risk management is becoming the dominant approach of flood control policies throughout Europe. This paper reviews the state-of-the-art and identifies research directions of economic flood damage assessment. Despite the fact that considerable research effort has been spent and progress has been made on damage data collection, data analysis and model development in recent years, there still seems to be a mismatch between the relevance of damage assessments and the quality of the available models and datasets. Often, simple approaches are used, mainly due to limitations in available data and knowledge on damage mechanisms. The results of damage assessments depend on many assumptions, e.g. the selection of spatial and temporal boundaries, and there are many pitfalls in economic evaluation, e.g. the choice between replacement costs or depreciated values. Much larger efforts are required for empirical and synthetic data collection and for providing consistent, reliable data to scientists and practitioners. A major shortcoming of damage modelling is that model validation is scarcely performed. Uncertainty analyses and thorough scrutiny of model inputs and assumptions should be mandatory for each damage model development and application, respectively. In our view, flood risk assessments are often not well balanced. Much more attention is given to the hazard assessment part, whereas damage assessment is treated as some kind of appendix within the risk analysis. Advances in flood damage assessment could trigger subsequent methodological improvements in other natural hazard areas with comparable time-space properties.**

KEYWORDS : Assessment, economic, flood, damage, design standards, structural

INTRODUCTION

1 Need for flood damage assessments

Traditionally, design standards and structural flood defence measures were the dominant flood management approaches. Structural flood defence measures, such as dikes and retention basins, were designed in order to control up to a certain, predefined design flood, e.g. a 100-year flood. In recent years, this “flood control approach” has increasingly been questioned. New concepts have been developed, usually referred to as “flood risk management” (Merz et al., 2010). The level of protection is determined by broader considerations than some predefined design flood while more emphasis is put on non-structural flood mitigation measures. An important development in this context is a focal shift from flood hazard to flood risk. Traditionally, flood policies concentrated on the control or reduction of flood hazard, i.e. decreasing the probability of occurrence and intensity of flood discharges and inundations. Flood risk management puts a much stronger emphasis on flood risk, where risk is defined as damage that occurs or will be exceeded with a certain probability in a certain time period (e.g. one year). Hence, damage aspects need to be taken into account in any deliberations on flood risk management.

Flood damage assessments are gaining more importance within this evolving context of decision-making in flood risk management. They are needed for

– *Assessment of flood vulnerability*: elements at risk in flood-prone areas, e.g. households or communities, are variably vulnerable to floods. For instance, communities which experience floods on a more or Published by Copernicus Publications on behalf of the European Geosciences Union.

less regular basis develop strategies for coping with such events. Communities which are not “flood- experienced” often neglect risk mitigation and, hence, develop a higher vulnerability (Thieken et al., 2007; Kreibich and Thieken, 2009). Knowledge about vulner- ability of elements at risk is necessary for identifying appropriate risk reduction measures, e.g. development of emergency plans and the undertaking of emergency exercises.

– *Flood risk mapping*: flood risk mapping is an essential element of flood risk management and risk communication. In many countries risk mapping is regulated by law. The Flood Directive of the European Union, enacted in November 2007, requires member states to create both flood hazard and flood risk maps (European Commission, 2007). Although flood mapping is frequently limited to mapping the flood hazard, there is a lively discussion on flood risk mapping, including the potentially adverse effects on asset values, people and the environment (de Moel et al., 2009).

– *Optimal decisions on flood mitigation measures*: safety against floods requires resources, among others large amounts of tax money. It should therefore be secured that these resources are well used economically. This implies that the current flood risk has to be estimated, the potential risk reduction options have to be deter- mined, and benefits and costs of different options have to be quantified and compared. For these steps to- wards cost-effective risk management, damage assessments are an essential ingredient.

– *Comparative risk analysis*: in a wider context, flood risk reduction competes with other policy fields dealing with risk reduction. For example, a municipality may be prone to different types of natural hazards. A quantitative comparison of different risks within a community or a region, e.g. risks due to flooding, windstorms and earthquakes, can be done on the basis of consistent damage and risk estimates (Gru¨ nthal et al., 2006). On a wider perspective, the allocation of resources devoted for safety against floods can be evaluated in terms of the social willingness-to-pay (Pandey and Nathwani, 2004).

– *Financial appraisals for the (re-)insurance sector*: to calculate insurance premiums and to guarantee solvency, expected economic damages and the probable maximum loss (PML)1 of the portfolios of insurers and re-insurers have to be estimated.

1 The terms loss and damages are often used interchangeably in the risk management of insurers. Acknowledging the differences between economic as well as physical loss and damage – for ex- ample, a damaged good is not necessary lost – we will restrict our usage of the term loss to either insurance contexts (where it is a terminus technicus) or to losses in substance such as loss of life or

loss of production.

– *Financial appraisals during and immediately after floods*: in the case of a flood event, disaster management and governments need assessments on the flood damage, in order to budget and coordinate decisions about damage compensation.

Although flood damage assessment is an essential part of flood risk management, it has not received much scientific attention. The consideration of flood damage within the decision-making process of flood risk management is still relatively new (Messner et al., 2007). Compared to the wealth of methods and available information on flood hazard, flood damage data are scarce and damage estimation methods are crude. This lack frequently leads to transfer of dam- age data and damage assessment models in time, space and across damage processes without sufficient justification.

This paper summarises the state-of-the-art, indicates short- comings and identifies research directions of economic flood damage assessments. It can be seen as complementary to the review report of Messner et al. (2007) who provide guide- lines for flood damage estimation meant for practitioners of governmental authorities and executing bodies dealing with ex-ante flood damage evaluation.

This paper is limited to economic flood damage. Ideally, flood risk assessments should comprise all damage dimen- sions including adverse social, psychological, political and environmental consequences, in order to obtain a compre- hensive damage picture. However, risk analyses are frequently limited to economic damages, either because other dimensions are seen of lesser importance or because the available methods are not able to derive reliable estimates. In case risk assessments do not take into account the complete spectrum of damages, the missing dimensions should at least be listed. Good starting points for risk to life assessment are Jonkman (2007) and for health impacts Tapsell et al. (2002), Hajat et al. (2003), and Ahern et al. (2005).

Although the paper focuses on flood damage assessment some issues, e.g. risk-based evaluation of mitigation measures, and methodological aspects of damage estimation are also valid for other natural hazards. A comparison of damage intensities scales across different natural hazards was given by Blong (2003a).

2 Basics of flood damage assessment

2.1 Types of flood damage

Flood damages can be classified into direct and indirect dam- ages. Direct damages are those which occur due to the physical contact of flood water with humans, property or any other objects. Indirect damages are induced by the direct impacts and occur – in space or time – outside the flood event. Both types of damages are further classified into tangible and in- tangible damages, depending on whether or not they can be assessed in monetary values (e.g. Parker et al., 1987; Smith and Ward, 1998). Tangible damages are damage to man- made capital or resource flows which can be easily specified in monetary terms, whereas intangible damage is dam- age to assets which are not traded in a market and are difficult to transfer to monetary values. Although the differentiation in direct and indirect, and tangible and intangible dam- age is commonplace, interpretations and delineations differ (Jonkman et al., 2007). Some examples for the different types of damage are:

– Direct, tangible: damage to private buildings and con- tents; destruction of infrastructure such as roads, rail- roads; erosion of agricultural soil; destruction of harvest; damage to livestock; evacuation and rescue measures; business interruption inside the flooded area; clean up costs.

– Direct, intangible: loss of life; injuries; loss of memorabilia; psychological distress, damage to cultural heritage; negative effects on ecosystems.

– Indirect, tangible: disruption of public services outside the flooded area; induced production losses to companies outside the flooded area (e.g. suppliers of flooded companies); cost of traffic disruption; loss of tax revenue due to migration of companies in the aftermath of floods.

– Indirect, intangible: trauma; loss of trust in authorities. The costs of direct impacts are generally easier to quantify than indirect costs. Indirect impacts may have effects on time scales of months and years. Further, cascades of higher- order impacts are conceivable such as macro-economic effects or long-term barriers to regional development in frequently flood-affected areas. Rose (2004) discusses the distinction between direct and indirect effects and concludes that this is a subject of great confusion. One has to be careful in order to ensure everything is counted while double-counting is avoided.

In some cases a distinction is made between potential and actual damage (e.g. Smith, 1994; Gissing and Blong, 2004). Actual damage is an estimate of the damage that occurred during a specific flood. Potential damage is defined as the damage that would occur in the absence of any damage reduction measures.

2.2 Spatial and temporal scales

Flood damage assessments are performed on different spatial scales:

– Micro-scale: the assessment is based on single elements at risk. For instance, in order to estimate the damage to a community in case of a certain flood scenario, dam- ages are calculated for each affected object (building, infrastructure object, etc.).

– Meso-scale: the assessment is based on spatial aggregations. Typical aggregation units are land use units, e.g. residential areas, or administrative units, e.g. zip code areas. Their size is in the order of magnitude of 1 ha to 1 km2 .

– Macro-scale: large-scale spatial units are the basis for damage estimation. Typically, administrative units are used, e.g. municipalities, regions, countries.

The classification in micro-, meso- and macro-scale is, on the one hand, related to the spatial extent of the damage assessment. On the other hand, there is a methodological distinction: Meso- and macro-scale approaches differ from micro-scale approaches in their need for aggregation. Dam- ages are assessed for aggregations of objects, e.g. land use units. In order to compare different-scale methods, upscaling and downscaling procedures for the different steps of damage assessment are necessary.

The results of a damage assessment depend on the spatial and temporal boundaries of the study. For example, a flood might devastate a community. At the same time, nearby communities might experience economic benefits, since the flood might trigger business and orders that cannot be performed by the flood-affected companies. For example, the 1993 US Midwest floods impeded barges to navigate the river. Be- cause of this lack of barge traffic, several trucking companies gained about 13 million US$ in additional revenue due to the increased demand for road transportation (Pielke, 2000). Other flood beneficiaries were farmers who translated good crops and elevated crop prices into a very successful year (Pielke, 2000). Similar considerations hold concerning the temporal scale. Flood can cause long-term consequences, such as health effects, which are not captured if a too short time horizon of the damage assessment is chosen.

The classification in micro-, meso- and macro-scale level has no clear-cut boundaries, and different analysts may set the boundaries in a different way. Closely linked to the spatial scale is the context of the damage assessment (purpose, required reliability, available data, available resources, etc.). Local studies, e.g. cost-benefit analysis for a single water defence structure, usually employ the micro-scale view and derive damage estimates for each flood-prone object. Since this approach requires detailed, local input data and a large effort per unit area, meso- and macro-scale approaches are frequently chosen to cover larger areas. Messner et al. (2007) give recommendations for the choice of the appropriate approach.

2.3 Basic economic principles

Economic evaluations of flood damages are purpose-related and therefore context-dependent. The rationales of economic evaluation are different in disaster relief programmes, for insurance contracts, or in public policy decisions. Disaster relief is assessed according to the individual need to recover after a flood which has disturbed daily practices. Insurance compensation is assessed based on previously agreed con- tract terms which promise different services from partial to full functional repair of damaged goods. Public policy evaluations intend to support decisions such as flood risk zoning and cost-benefit analysis of structural flood defence. They take a broader perspective of assessing potentially *all* costs and benefits to the national or regional economy, including impacts on intangible goods such as ecosystem services and public health.

Four basic principles of economic evaluation should be obeyed in order to conduct a damage assessment for public policy purposes in a consistent way. (A somewhat similar set of principles has been proposed by Messner et at., 2007).

Define the appropriate time and spatial boundaries of the study

A crucial choice for economic damage evaluation is the appropriate time and geographic extent over which flood effects are to be considered. Estimates of the immediate damages within the inundation area may be appropriate for assessing disaster relief programmes but fall short of a complete assessment of all costs to the regional or national economy. This is mainly so because indirect effects from transport or production disruptions are – by definition – occurring outside the inundation area. Some flood damage categories like effects on relocation of industries require the consideration of time spans which are much longer than those normally applied for direct damages. On the other hand, most indirect economic damages at the regional level disappear in a national or even international setting since regional production losses are compensated by production gains in regions outside the flooded area or even outside the watershed. Depending on the choice of the time and spatial boundaries, considerably larger or smaller indirect economic damages for a given flood scenario will be estimated. The most appropriate approach to this problem is to choose the time and spatial boundaries of the damage assessment in accordance with the time and spatial boundaries of the public policy project to be evaluated, e.g. the flood management project or the institutional out- reach of the planning authority. Federal planning should ac- count for all national direct and indirect effects whereas state planning or the planning of water authorities would only consider effects within the state or within the watershed. Best practice is to indicate any positive and negative transboundary impacts at least qualitatively in addition to the impacts assessed within the regional or executive boundaries.

Evaluate all tangible costs, including the cost of emergency services

Economists have since long developed methods to monetize damages to non-market goods, for example, life and limb (e.g. Mishan, 1971), amenities and ecosystem services (UBA, 2007), as well as other intangible damages associated with floods such as contingent valuation or hedonic price analysis. However, these methods are not widely accepted by practitioneers, in legal conflicts or flood risk management, because of the large variance of results and their sensitivity to study settings. Thus, there is a *pragmatic* choice to be made of what goods are treated as tangible or intangible in flood damage assessment. Tangible damages should include all direct and indirect damages that can be easily and undisputedly assessed in monetary terms. This should include the public spending for clean-up, evacuation and other emergency services. The costs for emergency services are easily measurable and can be accounted to the flood event (Penning-Rowsell and Wilson, 2006). Often those costs exceed the costs of direct flood damages (Morselt et al., 2007; Pfurtscheller and Schwarze, 2008). Sometimes they are the only damages of flooding – if emergency services are per- fectly effective in sheltering people and assets at risk. These costs should be regarded in the cost-benefit analysis of flood defence since they are affected by flood control measures in a similar way as flood damages to households, enterprises or public buildings.

Use depreciated values, not full replacement costs

Depreciated values of durable consumer goods reflect the value of a good at the time when the flood damage actually occurs, whereas replacement values usually involve some form of improvement: “Old goods which are damaged during a flood are substituted by new, more productive or better performing ones” (Penning-Rowsell et al., 2003). Using re- placement values overestimates the damage. Moreover it is not in line with the national accounting where capital goods are depreciated based on a perpetual inventory of incoming and outgoing capital goods (Schmalwasser and Schidlowski, 2006). The evaluation of flood damages at full replacement costs would systematically result in “values at risk” which are higher than the ones depicted in the national accounts. Therefore, the basic rule for public policy appraisal is: use depreciated values, not full replacement costs.

Occasionally, the replacement of goods by improved new ones can be cheaper than the repair of the goods in its original condition at the time when the flooding occurred. This is often the case with consumer durables that recently went out of production (e.g., single glass windows). For these types of goods replacement values should be used in economic evaluation if they undercut the costs of repair or monetary compensation at the depreciated original value.

Never sum up stock and flow values for one element at risk

From an economic point of view the value of a capital good is the present value of the income flow it generates over the rest of its life span (Georgescu-Roegen, 1981). Therefore, adding stock and flow values in a flood damage evaluation can lead to double counting (Rose, 2004; van der Veen and Logtmeijer, 2005; Bockarjova et al., 2007) and should be avoided. However, there are exceptions to this rule. If flow values for one element of risk (say, the loss of production during the flood event) are easier to be assessed than for other elements at risk (say, the lasting loss of functionality and increased need for attendance of a machine after a flood), than both stock and flow values may be used in the economic evaluation as long as each individual element of risk is clearly separated (Messner and Green, 2007).

3 Direct monetary damages

3.1 General procedure

The most frequently used procedure for the assessment of direct monetary flood damage comprises three steps:

1. Classification of elements at risk by pooling them into homogeneous classes.

2. Exposure analysis and asset assessment by describing the number and type of elements at risk and by estimating their asset value.
3. Susceptibility analysis by relating the relative damage of the elements at risk to the flood impact.

This three-step procedure holds for the relative damage approach, where the damage share or relative damage is used. Alternatively, the absolute damage approach is based on the absolute monetary amount of damages per risk element or unit (e.g. square meter). In this case steps 2 and 3 are combined within a single damage function.

3.2 Classification of elements at risk

3.2.1 Rationale for classification

Depending on the spatial extent of the investigated inundation area and the chosen degree of detail of the damage assessment, a large number of elements at risk has to be considered. In general, it is not possible to assess the damage for each single object, because there is no information on the damage behaviour of each object and/or because such a detailed assessment would require a huge effort. Therefore, elements at risk are pooled into classes, and the damage assessment is performed for the different classes, whereas all elements within one class are treated in the same way. For example, in the assessment of flood damage to private house- holds, all households of a certain type may be grouped in one class and may obtain the same asset value, e.g. related to the floor area. Similarly, the relative damage of all households in this class may be estimated by using the same susceptibility function.

One of the tasks of damage assessment is therefore to decide on the details of classification. Which objects should be pooled together? Ideally, within each class, there should be a minimum of damage variance for a given flood impact, and there should be a maximum of variance in damages be- tween classes. To our knowledge, there are currently no classifications in flood damage assessments which are based on objective or statistical classification methods. Expert judgement currently determines the details of classification and the derivation of class boundaries.

Figure 1 schematically depicts the relation between the detail of classification and the main influencing factors. Decisive are the resources that can be spent for the assessment. A higher level of classification requires a larger effort. This factor is related to the necessary detail of the study, although it is not given that a higher level of classification always leads to higher reliability of the damage assessment. This is only the case, if the higher number of estimates of assets and susceptibility is supported by sufficient data. A very detailed damage assessment based on sparse data may be misleading, since this involves a level of accuracy which may not be given. Therefore, the availability of data for the estimation of assets and susceptibility is another decisive aspect. In this respect, it has to be noted that it is necessary to ascribe any individual element at risk to the appropriate class with a minimum of work. In addition, secondary source data, such as property valuations, may have their own system of classification and so the classification used for elements at risk must be capable of being linked to existing data sources.

Further, the uniformity of the socio-economic structure of the study area influences the detail of classification. More uniform areas require fewer classes. For example, Smith (1994) argues that while there are broad similarities between house types and average contents throughout much of Australia this does not hold for the UK where dwelling types vary markedly. Neither does it hold for countries with wide variations in household income. The heterogeneity of the flood impact within the study area could influence the detail of classification as well. For example, Kreibich and Thieken (2008) and Kreibich and Dimitrova (2010) have shown that relative damage functions may not hold for different types of inundation (fluvial flood, flash flood, flooding as consequence of high groundwater, inundation as consequence of dike breaching). Therefore, classification according to flood impact could also be useful.

The detail of the classification of a damage assessment should be in line with the relevance of the objects or classes. There is a tendency to use a coarse classification and very simple models for sectors with little data. This is problem- atic if these sectors possess a high damage potential. A small share of flooded objects often causes a large share of damage. A single large industrial plant can incur direct flood damage that exceeds that for several hundred nearby dwellings subject to the same flood risk. For instance, the winter flood in 1993 in the Seckach catchment in south-west Germany caused damages at several hundreds of objects in 19 communities. 40% of the direct damage emerged from a single industrial premise. A Pareto-like distribution of damages, e.g. 20% of the affected objects is responsible for 80% of the total damage, is frequently observed in damage data.

3.2.2 Commonly adopted classification approaches

In most cases the classification is based on economic sec- tors, such as private households, companies, infrastructure and agriculture, with a further distinction into sub-classes. This is based on the understanding that different economic sectors show different characteristics concerning assets and susceptibility. For example, elements at risk of the residential sector are mainly buildings; this is only partly the case in other sectors like the commercial, agricultural or public sector. Further, flood impact varies between sectors. For ex- ample, flood damage to residential buildings is strongly dependent on the water depth of a flood, whereas for damage to agricultural crops the time of flooding and the duration of the flood are decisive (Fo¨ rster et al., 2008). A pragmatic reason for using economic sectors as classification criterion is that economic data which are needed for estimating the value of elements at risks are usually aggregated according to economic sectors.

Table 1 gives a typical classification in economic sectors and short remarks on their characteristics. These examples show that the elements at risk within one economic sector may be very diverse. Therefore, most damage assessments introduce sub-classes. For example, recently in Ger- many the damage models FLEMOps and FLEMOcs have been developed for the private and the commercial sector, respectively (Thieken et al., 2008a, b; Kreibich et al., 2010). FLEMOps, the model for the private sector, differentiates into three building type classes (one-family homes, (semi-)detached houses, multi-family houses) and two building quality classes (low/medium quality, high quality). Similarly, FLEMOcs distinguishes among three classes concerning company size in respect to the number of employees (1–10, 11–100, >100 employees) and among four subsectors (public and private services, producing industry, corporate services, trade). Even with such sub-classes the variability of objects within one sub-class is large. Therefore, as- set estimates and damage functions that are given for a certain sub-class are expected to describe only a rather limited share of the variability that is observed in damage data. How- ever, finer classifications require more data and/or information which are usually not available.

An interesting classification approach has been developed by Schwarz and Maiwald (2007, 2008). It classifies the building stock according to the structural characteristics of buildings. The main building types are clay, prefabricated, framework, masonry, reinforced concrete and flood resistant designed buildings. For each building type a relationship between flood impact and damage grade is derived based on damage observations and engineering judgement. Damage is classified from damage grade DG1 (only penetration and pollution) to damage grade DG5 (collapse of the building or of major parts of the building; demolition of building required). In a second step damage grades are translated into monetary damage. This structural engineering approach is appealing since it allows, in principle, to consider physical processes at the building level. For example, the impact of flow velocity is very different for masonry and reinforced concrete. The approach of Schwarz and Maiwald (2007, 2008) requires information on the building stock which can be easily obtained for single buildings. However, for large-scale damage assessments, this information is not available and can only be collected with a very large effort. Therefore, some kind of regionalization approach to estimate the building type is necessary. The work of Deilmann (2007) points to this direction. He proposes to derive a building typology for the building stock and to link this typology with so-called urban structural types. These are areas with characteristic formations of buildings and open spaces, under consideration of regional peculiarities. Urban structural types form different patterns within the urban fabric. The idea is to assign damage functions and refurbishment costs to these urban structural types.

3.3 Exposure analysis and asset assessment

Exposure analysis identifies objects that are affected by a certain flood scenario. Exposed objects are commonly extracted by intersecting land use data with inundation data by means of operations within a geo information system. In order to achieve quantitative estimates of the exposed value (or value at risk), asset values have to be estimated for all flood-affected objects. Asset values depend on the type of the elements at risk, but also vary in time and space. The variation in time can be attributed to economic trends, e.g.

Table 1. Possible classification of elements at risk according to economic sectors.

Sector	Examples	Remarks
Private households	Residential buildings including contents, garages, summer houses etc., privately used vehicles	Majority of data sets and approaches exist for this sector. Variation of assets and susceptibility is rather low compared to other sectors.
Industry, manufacturing	Mining, metal processes, car and mechanical engineering industry, chemical industry, construction industry, installers workshop, carpentry, etc.	High variability and little data available. Transfer of asset values and damage functions within sector is problematic. Booysen et al. (1999) argue that it is not possible to develop standard damage function for industries and that questionnaires have to be provided for each industrial plant.
Services sector	Retail trade, wholesale trade, credit and insurance institutions, hotel and restaurant industry, lawyers, software companies, etc.	Rather high variability and little data available. Transfer of asset values and damage functions within sector has to be done with care.
Public sector	Education and culture (schools, universities, theaters, etc.), recreation and sports (camps and sports hall, etc.), administration, health care and social welfare (hospitals, nursing home, etc.), churches	High variability and little data available. Transfer of asset values and damage functions within sector is problematic.
Lifelines and infrastructure	Water supply, sewerage and drainage, gas supply, power supply, telecommunication, transportation	Little data available. Transfer of asset values and damage functions possible within certain classes, e.g. unit values and damage functions for roads of certain characteristics.
Agriculture	Loss of crops, damage to buildings, contents, machinery; soil erosion, loss of livestock	Methods and data availability comparatively good. Average values per element at risk might be suitable in countries where this sector has a small damage potential compared to other sectors.
Others	Damage to flood defence structures; clean-up costs, evacuation and disaster management costs	Little data available. Average values are often used, e.g. average costs of evacuation (Penning-Rowsell and Green, 2000), but do not hold in the context of multiple hazards (Pfurtscheller and Schwarze, 2008).

inflation, new investments and innovation. While inflation can be corrected by price indices, other changes in time can only be absorbed by a regular update of the data base. Variation in space occurs because the same object type has a different asset value in one region than in another due to regional specifications or differences in material costs, wages, etc. This variation can be covered by the use of regional or local data instead of national data.

Within one type of element at risk, e.g. a residential home or a company site, several categories of assets can be identified. Usually the value of the building fabric (fixed assets) and the value of the contents (moveable items) are distinguished. In the commercial and industrial sector the contents are further divided into machinery and equipment on the one hand and products, goods or stocks on the other hand. As their susceptibility varies (e.g. in case of a flood, fixed assets cannot be removed from the flooding zone, whereas move- able items such as products can be secured) and since they contribute with different proportions to the total asset value, the asset values of these categories should be estimated separately. In some cases the exposure data, e.g., the data base by Kleist et al. (2006) and Thieken et al. (2006), were not only used for flood risk analyses, but also for the estimation of damages due to windstorms (Heneka et al., 2006) and earth- quakes (Tyagunov et al., 2006).

There are not many risk assessment studies in the literature that explicitly explain approaches for the estimation of as- sets. This might be due to the fact that in many risk analyses no quantitative risk indicators are used or that damage modelling is done with absolute damage functions. In such cases, land use/cover data are used to describe exposure in terms of affected sectors or economic activities, but they do not give a monetary value. In approaches that estimate monetary asset values (see Table 2), two steps can be distinguished. First, exposure (or asset) data are estimated on a coarse level, e.g. on the level of municipalities (Kleist et al., 2006; Seifert et al., 2006) or census blocks, e.g. in HAZUS-MH (FEMA,2003). In some cases, official statistics, e.g. on population, can be directly used as exposure data. For risk analyses, a disaggregation of these coarse values has to be done in order to overcome the spatial mismatch between hazard and expo- sure data (Chen et al., 2004).

Table 2. Examples of approaches for the estimation of exposure data. (CORINE stands for Coordination of Information on the Environment.)

Models (references)	Country	Approach	Scale	Sectors
Unit Values [€/m2]	Germany	Gross stock of fixed assets	Meso	All, except for residential
derived from stock data	(North Rhine-	in combination with land use data		sector (distinction in immobile
MURL (2000),	Westphalia,	(land register ATKIS)		(e.g. buildings) and mobile
Gru¨ nthal et al. (2006)	Cologne)			(e.g. machinery, inventory)
				asset values)
Mean insured value	Germany	Total asset per community is estimated	Meso	Residential sector
MURL (2000),	(North Rhine-	by multiplying the number of buildings with		(distinction in immobile
Gru¨ nthal et al. (2006)	Westphalia, Cologne)	their mean insurance value; transfo rmation to a unit value [€/m2] by relating		(e.g. buildings) and mobile (e.g. machinery, inventory)
		the sum to the total settlement area		asset values)
Rhine-Atlas	Rhine Valley	Modified approach of MURL (2000) in	Meso to	All sectors (distinction
(ICPR, 2001)	(France,	combination with CORINE land cover data;	macro	in immobile and
	Germany,	transfer from Germany to other countries		mobile asset values)
	Netherlands,	by matching coefficients derived from		
	Switzerland)	gross domestic		
		products		
Standardised	Germany	Combination of standardised construction costs	Meso	Residential sector
building		for residential buildings in Germany with		(building asset values)
construction		census data about the building stock and		
costs with		the living area per community resulting in		
dasymetric mapping		the total as well as the percapita replacement		
Kleist et al. (2006),		costs for residential buildings, differentiated		
Thieken et al. (2006)		by type, for all communities in Germany.		
		A spatially-distributed inventory was provided by		
		dasymetric mapping adapted from Gallego and		
		Peedell (2001) based on CORINE land cover data.		
Branch-specific	Germany	Derivation of branch-specific asset values for	Meso	60 commercial and
assets with		three sizes of production sites and 60 economic		industrial sectors
dasymetric mapping		activities based on stock data; municipal values		(mobile and immobile;
Seifert et al. (2010)		were further disaggregated with the help of		gross/net values)
		CORINE land cover data and a mapping		
		approach modified		

HAZUS-MH	USA	Building asset values were estimated	Meso	Commercial and
(FEMA, 2003;		by multiplying the total floor size of		industrial sector
Scawthorn et al., 2006)		a building occupancy in a census block,		(16 different building
		which reflects to a certain degree the typ of		occupancies)
		economic activity and was assumed to be		
		uniform, with the building replacement costs per		
		square foot in this census block. Depreciated		
		values are derived from data about building costs		
		and consider the age and the condition		
		of the structure. Contents asset values are		
		estimated as a fixed percentage of the building		
		asset value.		

In contrast to information on the exposed assets, hazard estimates like water depths or inundation areas are commonly modelled at a spatially explicit raster level. Macro-scale approaches may simply assume an equal spatial distribution of the provided assets over the whole administrative area. Within mesoor micro-scale studies, however, the different assets have to be disaggregated to achieve a more realistic distribution. In general, disaggregation is defined as a process of transferring the value of a (statistical) variable from a coarse spatial level to a lower spatial level by means of ancillary information (Meer and Mosimann, 2005; Wenkel and Schulz, 1999). As far as mapping is concerned, disaggregation is also addressed as dasymetric mapping or regionalisation (e.g. Chen et al., 2004; Meyer, 2005).

Different disaggregation methods using an ancillary data set with better spatial information have already been developed and applied in former studies concerning not only dam- age estimation for various natural hazards, but particularly

Table 2. Continued.

Models (references)	Country	Approach	Scale	Sectors
Unit economic values combined with aerial photographs (Dutta et al., 2003)	Japan	To assess the monetary values for property and inventory of non-residential objects, the number of no n-residential objects, the number of workers per type was multiplied by unit prices per worker and type. The values of residential buildings were estimated by the product of the unit area with the structure value per unit area and the content value per unit area, respectively. Calculations are done on ward-level; for further spatial disagg regation the floor area per grid cell was determined considering land cover type, building ratios and floor area fractions derived from aerial photographs	Mirco	Residential sector and eight non-residential types of economic activity (mining; construction; production; el ectricity/gas/ water; wholesale and retail sale; finance and insurance; real estate; services)
Construction cost ratios Blong (2003b)	Australia	Construction costs (replacement costs) per square meter of different building types as published by	Micro	All building types

the Australian authorities are related to construction costs of a medium-sized family house (cost ratios). Differences in the building size (floor area) are considered by a replacement ratio (RR = [(Cost Ratio∗Floor area)/Floor area of a medium-sized family house)]. Replacement ratios are used in the damage model which calculates damage as house equivalents. Monetary damage is achieved by multiplying the house equivalents by the costs of a medium-sized family house.

mapping of population density (Eicher and Brewer, 2001; Gallego and Peedell, 2001; ICPR, 2001; Mennis, 2003; Chen et al., 2004; Meyer, 2005; Thieken et al., 2006; Seifert et al., 2010). In these studies topographic maps, traffic networks, satellite or land use and land cover data sets have been proven suitable for disaggregation purposes, since their information has an implicit relation to population and, therefore, to asset distribution as well. For example, Dutta et al. (2003) used grid cell basis land cover data to disaggregate exposure data that were estimated on ward-level. In this approach, the floor area per grid cell was determined considering land cover type, building ratios (i.e. the percentage of area covered by buildings in a given area) and floor area fractions (i.e. the total area of all storeys of a building divided by the ground surface area of the building; thus for a one-storey building the floor area fraction amounts to 1). The latter two parameters were derived from aerial photographs. This approach is feasible for small or medium sized areas, but not for a countrywide approach, since the analysis of aerial photographs for a huge area would be too time-consuming. Other approaches as shown in Thieken et al. (2006) and Seifert et al. (2010) are also applicable in large areas. Wu¨ nsch et al. (2009) compared three different disaggregation methods and two land use data sets in the framework of damage estimation and concluded that it is better to invest in land use data than in more sophisticated mapping techniques.

Even if disaggregation is performed, exposure data contain further uncertainties. For example, in the model HAZUS- MH uniform distribution of the buildings within a census block and, thus, of the asset values is assumed. The smallest unit in the HAZUS-MH asset data base is therefore the census block. As each census block should cover approximately the same number of inhabitants, the census blocks vary extremely in extent, i.e. from a few city blocks in urban areas to several square miles in rural areas. In urban areas with high building density the assumption of an uniform building distribution holds true with few exceptions (e.g. roads or parks), but in rural areas the building density is low and the assumption is questionable and may lead to a large error in the spatial distribution of asset values. This problem can only be solved if data from a sub-scale are taken into account (Meyer, 2005; Wu¨ nsch et al., 2009).

This overview shows that the methods for asset estimation vary considerably in terms of detail concerning the stratification in economic classes and the spatial disaggregation of lumped values. The detail of asset estimation depends strongly on the size of the study area, the available input data and the required accuracy of the risk assessment.

3.4 Susceptibility analysis

A central idea in flood damage estimation is the concept of damage functions. They relate damage for the respective element at risk to characteristics of the inundation. These functions represent the susceptibility of the respective element at risk, similar to dose-response functions or fragility curves in other safety-relevant fields. Most flood damage models have in common that the damage is obtained from the type or use of the element at risk and the inundation depth (Wind et al., 1999; NRC, 2000). Other parameters, like flow velocity, duration of the inundation and time of occurrence are rarely taken into account. Such stage-damage curves or depth-damage curves were proposed in the USA (White, 1945, 1964) and they are seen as the standard approach to assessing urban flood damage (Smith, 1994).

3.4.1 Damage influencing parameters

It is obvious that flood damage depends, in addition to the type of object and water depth considered by stage-damage curves, on many factors. Some of these factors are flow velocity, duration of inundation, sediment concentration, contamination of flood water, availability and information con- tent of flood warning, and the quality of external response in a flood situation. Although a few studies give some quantitative hints about the influence of these factors (Smith,1994; Wind et al., 1999; Penning-Rowsell and Green, 2000; Kreibich et al., 2005, 2009; Thieken et al., 2005), there is no comprehensive approach for including such factors in dam- age modelling.

Damage influencing factors can be differentiated into im- pact and resistance parameters (Thieken et al., 2005). Impact parameters reflect the specific characteristics of a flood event for the object under study, e.g. water depth, flow velocity, contamination. Whereas impact parameters depend on the kind and magnitude of the flood, resistance parameters depend on characteristics of the flood prone objects. They depict the capability or incapability of an object to resist the flood impact. Resistance parameters can be the object size or the type and structure of a building. Further, also mitigation measures, former flood experience and early warning influence the resistance (Kreibich et al., 2007). Table 3 com- piles damage influencing factors that have been considered in flood damage assessments.

Most of these damage influencing factors are neglected in damage modelling, since they are very heterogeneous in space and time, difficult to predict, and there is limited information on their (quantitative) effects. For instance, a gate be- ing opened could make the difference between high and low flow velocities and, as a consequence, scour undermining a foundation or not (Kelman and Spence, 2004). Floating and destruction of an oil-tank can make the difference between total damage of a building due to severe contamination or marginal damage due to water contact only.

The influence of these factors on the damage was tested separately in most studies. However, damage susceptibility depends on many factors, which are not independent from each other. For example an early warning can not work, if the meaning of the warning is not recognized by the affected people due to a lack of preparedness, or if mitigation measures are impossible due to an extreme flood impact. Thus, multivariate analyses are necessary. However, such analyses undertaken by McBean et al. (1988) did not lead to clear-cut results and let them conclude: “In all likelihood, the factors considered here and many others combine to determine the level of flood damage that may be experienced in any house- hold. It does not however seem possible to develop a simple and practical predictive tool that incorporates these factors”.

3.4.2 Damage functions

In developing flood damage models two main approaches can be distinguished: empirical approaches which use dam- age data collected after flood events and synthetic approaches which use damage data collected via what-if-questions. An example for the first approach is the German flood dam- age data base HOWAS (Merz et al., 2004), from which the damage functions of MURL (MURL, 2000) and Hydrotec (Emschergenossenschaft and Hydrotec, 2004) were derived. What-if analyses estimate the damage which is expected in case of a certain flood situation, e.g.: “Which damage would you expect if the water depth was 2 m above the building floor?” Examples for this approach are the damage func- tions for United Kingdom (Penning-Rowsell et al., 2005). It is possible to combine both approaches, e.g. to extend empirical data with synthetic data which was done by the US Army Corps of Engineers (USACE, Galveston District, Texas, personal communication, 2006), in Australia (NRE,2000; NR&M, 2002) and Germany (ICPR, 2001) or to eval- uate synthetic models with empirical data. Both approaches have advantages and disadvantages (Table 4).

Besides the choice of empirical or synthetic damage functions, a choice has to be made between relative or absolute functions. Table 5 compares the advantages and disadvantages of both options. Which of both approaches is chosen may depend on the kind of available data, e.g. on the avail- ability of data on the value of assets (Messner et al., 2007). Absolute damage functions are applied, for instance, in the UK (Penning-Rowsell et al., 2005) or in Australia (NR&M,2002; NRE, 2000). Relative damage functions are used, e.g., in the model HAZUS-MH in the USA (FEMA, 2003; Scawthorn et al., 2006) and for damage estimations along the river Rhine (MURL, 2000; ICPR, 2001). A further possibility are index values, e.g. the damage may be expressed as an equivalent to the number of median-sized family houses totally destroyed (Blong, 2003b).

Table 3. Examples of damage influencing factors considered in different flood damage assessments (adapted/extended from Gissing and Blong, 2004; Kelman and Spence, 2004; Merz, 2006; Fo¨ rster et al., 2008).

Impact parameter

Parameter	Description	Selected references
Inundation depth	The higher the inundation depth, the greater the building and contents parts which are damaged and the stronger the buoyancy force.	CH2M Hill (1974); Black (1975), Sangrey et al. (1975), Smith and Tobin (1979), Handmer (1986), Smith (1991), Torterotot et al. (1992), Smith and Greenaway (1994), Hubert et al. (1996), USACE (1996), Islam (1997), Blong (1998), Zerger (2000), Nicholas et al. (2001), Beck et al. (2002), Kato and Torii (2002), Citeau (2003), Dutta et al. (2003), Hoes and Schuurmans (2005), Penning-Rowsell et al. (2005), Bu¨ chele et al. (2006), Kreibich and Thieken (2008), Thieken et al. (2008a)
Flow velocity	The greater the velocity of floodwaters, the greater the probability of structural building damage due to lateral pressure, scouring, etc. High flow velocities can cause direct damage to crops and may lead to soil degradation from erosion	CH2M Hill (1974), Black (1975), Sangrey et al. (1975), Smith and Tobin (1979), Handmer (1986), McBean et al. (1988), Smith (1991), Smith and Greenaway (1994), USACE (1996), Islam (1997), Blong (1998), Zerger (2000), Nicholas et al. (2001), Beck et al. (2002), Kato and Torii (2002), Citeau (2003), Schwarz and Maiwald (2007, 2008), Kreibich et al. (2009), Pistrika and Jonkman (2009)
Duration of inundation	The longer the duration of inundation, the greater the saturation of building structure and contents, the higher the effort for drying, the more severe the anoxia of crops, increasing the probability of damage.	Smith and Tobin (1979), Handmer (1986), McBean et al. (1988), Torterotot et al. (1992), Consuegra et al. (1995), Hubert et al. (1996), USACE (1996), Islam (1997), Nicholas et al. (2001), Kato and Torii (2002), Citeau (2003), Dutta et al. (2003), Penning-Rowsell et al. (2005), Fo¨ rster et al. (2008)
Contamination	The greater the amount of contaminants, the greater the damage and the cleanup costs. Inclusion or adsorption of contaminants may even lead to total damage. Examples are the inclusion of small particles in porous material impossible to remove, or the dispersal of microorganisms in moist building material requiring extensive clean up and disinfection.	Smith and Tobin (1979), Handmer (1986), USACE (1996), Nicholas et al. (2001), Kreibich and Thieken (2008), Thieken et al. (2008a)
Debris/ sediments	The presence of debris in floodwater, depending on its amount, size and weight, increases the dynamical forces which affect buildings and thus the potential for structural damage. Sediment can damage flooring and mechanical equipment and it may lead to an increased effort for clean up.	Handmer (1986), Penning-Rowsell et al. (1994), Kato and Torii (2002)
Rate of rise	As the rate of rise	Smith and Tobin

increases, it becomes increasingly difficult to reduce flood damage.
(1979), Handmer (1986), Penning-Rowsell et al. (1994)

Frequency of inundation	Repeated flooding may have cumulative effects, increasing the probability of damage. On the other hand, preparedness significantly increases, leading to reduced damage.	USACE (1996), Elmer et al. (2010)
Timing	Floods occurring at night may be associated with greater damage owing to ineffective warning dissemination. Floods occurring during holidays may see property owners absent and unable to take damage-reduction measures. The time of year (season) of flood occurrence with respect to crop growth stages and critical field operations plays a crucial role for the magnitude of agricultural damage.	Smith and Tobin (1979), Smith and Greenaway (1984), Smith (1992), Smith (1992), Consuegra et al. (1995), Yeo (1998), Citeau (2003), Dutta et al. (2003),

Table 3. Continued.

	Resistance parameter	
Parameter	Description	Selected references
Business sector/ use of building	Sectors differ significantly in respect to exposed assets as well as susceptibility. For instance, the manufacturing sector has a relatively high damage potential (high assets and business volumes) but a relatively good preparedness status. In contrast, preparedness is comparatively weak in the financial and service sectors.	MURL (2000), ICPR (2001a), FEMA (2003), Emschergenossenschaft and Hydrotec (2004), Penning-Rowsell et al. (2005), Scawthorn et al. (2006)
Building type	Building type may significantly influence the degree of damage. For instance, multistory buildings are affected by a lower fraction in contrast to single-storey buildings. Additionally, their relation of weight to buoyancy force is	Penning-Rowsell et al. (2005), Bu¨ chele et al. (2006), Kreibich and Thieken (2008), Thieken et al. (2008a)

Building material	Building material reacts differently to exposure to (contaminated) water, e.g. absorbents rates are different. Additionally, drying of material as well as decontamination is more or less difficult. Building material affects also the weight of the building and thus the danger of buoyancy.	Nicholas et al. (2001), Schwarz and Maiwald (2007, 2008)
Precaution	There are various precautionary measures, which are able to reduce flood damage significantly. Examples are constructural measures such as elevated building configuration, use of suitable building material or flood adapted interior fitting. Measures like flood secure configuration of oil tanks or secure storage of chemical can prevent contamination.	Kreibich et al. (2005), Bu¨ chele et al. (2006), Kreibich and Thieken (2008), Thieken et al. (2008a)
External response/ emergency measures	Emergency measures can be undertaken particularly effective with sufficient warning time and low water levels. Such measures are for instance the dismounting of fixed equipment/machinery, the relocation of inventory, the sealing of openings to prevent water from entering the building. Or quick drying or disinfection which reduce mold building on walls.	
Early warning	Only if the warning time is sufficiently long and if the content is comprehensible, emergency measures can be undertaken efficiently.	McBean et al. (1988), NRE (2000), Penning-Rowsell et al. (2005)

3.5 Examples for different economic sectors

In the following, a few economic sectors are described exemplarily. This compilation shows that a wide spectrum of approaches is found among damage models. Given this model heterogeneity, aspects of model reliability, calibration and validation are very important.

3.5.1 Residential sector

Most flood damage data, analyses as well as damage models refer to the residential sector. Here, only three models are presented exemplarily to illustrate different development strategies, function types and number of parameters (Table 6). The model of the Multicoloured Manual for UK is based on synthetic damage data and uses absolute dam- age functions (Penning-Rowsell et al., 2005). In contrast, FLEMOps is based on empirical damage data and uses rela- tive damage functions (Bu¨ chele et al., 2006; Thieken et al.,

Table 4. Advantages and disadvantages of empirical and synthetic flood damage models.

	Advantages	Disadvantages
Empirical damage models	Real damage information possesses a greater accuracy than synthetic data (Gissing and Blong, 2004).	Detailed damage surveys after floods are uncommon, so that models may be based on poor quality data (Smith, 1994).
	Effects of damage mitigation measures can be quantified and taken into account in damage modelling (Kreibich et al., 2005; Thieken et al., 2008a).	Paucity of information about floods of different magnitude and often a lack of damage records with high water depth require extrapolations (Smith, 1994; Gissing and Blong, 2004).
	Variability within one category and water depth is reflected by the data and uncertainty can be quantified (Merz et al., 2004).	Transferability in time and space is difficult due to differences in warning time, flood experience, building type and contents (Smith, 1994).
Synthetic damage models	In each building, damage information for various water levels can be retrieved (Penning-Rowsell and Chatterton, 1977).	High effort is necessary to develop detailed data bases (inventory method) or undertake large surveys (valuation survey method) to achieve sufficient data for each category/building type (Smith, 1994).
	Approach does not rely on information from actual flood events and can therefore be applied to any area (Smith, 1994).	What-if analyses are subjective, resulting in uncertain damage estimates (Gissing and Blong, 2004; Soetanto and Proverbs, 2004)?
	Higher level of standardisation and	Mitigation actions are not taken into account

comparability of damage estimates (Smith, 1994) . Premises within one classification can exhibit large variations which are not reflected by the data (Smith, 1994).

Table 5. Advantages and disadvantages of relative and absolute damage functions.

	Advantages	Disadvantages
Relative damage functions	Simplicity, because many data sources on the value of properties are available (Messner et al., 2007).	Values of the object assets are necessary. Their estimation might bring in additional uncertainty.
	Better transferability in space and time, since they are independent of changes in market values of individual structures which may result from inflation, shifts in local economy or development status (Krzysztofowicz and Davis, 1983).	
	Applicable for different purposes (cost-benefits analyses as well as PML-studies for insurances; only asset data base has to be altered).	
Absolute damage functions	No need for asset values, the estimated monetary damage due to a given flood scenario results directly.	Need for regular recalibration, e.g. damage functions of Penning-Rowsell and Chatterton (1977) were re-calibrated, reflecting larger investments in properties and contents (Penning-Rowsell and Green, 2000).
		Depend on the total value of the affected object.

2008a). The relative damage model of the ICPR is based on a combination of empirical and synthetic damage data (ICPR, 2001). The models differ greatly in the number of influencing parameters used. The model of the ICPR exclusively takes the water depth into account to estimate the immobile and equipment damage of settlements. Additionally,

Table 6. Comparison of three exemplary damage models for the residential sector.

Models (references)	Country	Development	Functions	Parameters	Damage type
Model of Multicoloured	UK	synthetic	absolute	water depth, flood duration,	building fabric items, household

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building type, building age, social class of the occupants
Manual (Penning-Rowsell et al., 2005)

FLEMOps (Bu¨ chele	Germany	empirical	relative	water depth,	building and contents

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		et al., 2006; Thieken et al., 2008) contamination, building type, quality of building, precaution						
			Model of ICPR	Germany	empirical-synthetic	relative	water depth	immobile, equipment,

		(ICPR, 2001)	mobile	

3.5.2 Industrial sector

Models for the estimation of direct damages of companies differ concerning their development, their functions, the parameters they include and the damage types they estimate (Table 7). Most of these model characteristics have been discussed before in Sect. 3.4. However, some aspects are specific for damage models for the industrial sector. With respect to the resistance parameters considered, especially the number of differentiated object types varies greatly. While the US-model HAZUS-MH (FEMA, 2003) distinguishes 16 main company types with several subclasses for damages to buildings, RAM (NRE, 2000) does only differentiate in companies smaller or larger than 1000 m2 . Concerning the classification of companies, the German models listed in a stage-damage function is given for mobile damages of set- tlements, which consist of 35% economic assets, 60% residential assets and 5% public goods (ICPR, 2001). Figure 2 shows this function and two other depth-damage-curves that are frequently used in Germany. The model of the Multicoloured Manual takes into account 14 water depth levels and two duration classes (Penning-Rowsell et al., 2005). Additionally, five house types, seven building periods and four different social classes of the dwellings' occupants are considered. The weighting of damages by the social class is applied to correct for lesser damages in properties occupied by the less affluent and therefore the lower benefits that these properties, by themselves, can generate (HM Treasury,2003). FLEMOps differentiates between five water depth classes, three contamination classes, three building types, two building qualities and three precaution

Table 7 follow the European nomenclature of economic ac- tivities (NACE; Eurostat, 2008), whereas the other models use a more functional classification approach. Variations between the models can also be found regarding the company size as resistance parameter: HAZUS-MH includes a size- factor in its object classification (e.g. small, medium, large warehouses). Anuflood relates company size to the building floor space (see Scawthorn et al., 2006; NR&M, 2002 for details). FLEMOcs distinguishes three sizes of companies in relation to their number of employees (Kreibich et al., 2010). Some models separately estimate damages to different asset types, e.g. the functions developed by the US Army Corps of Engineers, which are partly used in HAZUS-MH (FEMA, 2003; Scawthorn et al., 2006), distinguish damages at buildings, inventory and equipment (USACE, personal communication, 2006). FLEMOcs distinguishes damages at buildings, equipment and goods, products, stock (Kreibich et al.,2010), and the ICPR (2001) and the Saxon Agency of Environment and Geology (LfUG, 2005) estimate separately damages to buildings, immobile inventory and mobile inventory. Other models, e.g. Hydrotec (Emschergenossenschaft and Hydrotec, 2004), Anuflood (NR&M, 2002) and RAM (NRE, 2000), simply estimate the total damage of all asset types.

Table 7. Comparison of different damage models for the industrial sector (adapted from Kreibich et al., 2010).

Models (references)	Country	Development	Functions	Parameters	Loss type
Anuflood (NR&M, 2002)	Australia	empirical	absolute	water depth, object size, object susceptibility	total
RAM (NRE, 2000)	Australia	empirical-synthetic	absolute	object size, object value, lead time, flood experience	total
FLEMOcs (Kreibich et al., 2010)	Germany	empirical	relative	water depth, contamination, business sector, number of employees, precaution	building and equipment and goods, products, stock
Model of MURL (MURL, 2000)	Germany	empirical	relative	water depth, business sector	building and inventory
Model of Hydrotec (Emschergenossenschaft and Hydrotec, 2004)	Germany	empirical	relative	water depth, business sector	total
Model of ICPR (ICPR, 2001)	Germany	empirical-synthetic	relative	water depth, business sector	building and mobile and immobile inventory
Model of LfUG, Saxony (LfUG, 2005)	Germany	empirical-synthetic	relative	water depth *or* specific discharge, business sector	building and mobile and immobile inventory
Model of Multicoloured manual (Penning-Rowsell et al., 2005)	UK	synthetic	absolute	water depth, flood duration, object type, lead time	total
HAZUS-MH (FEMA, 2003; Scawthorn et al., 2006)	USA	empirical-synthetic	relative	water depth, object type	building and equipment and inventory

3.5.3 Infrastructure

Damage to infrastructure comprises a variety of potentially affected structures and different damage types. Potentially affected structures are public utilities (lifelines) such as water supply, sewerage and drainage, gas and power supply and telecommunication. Further, damage to transportation facilities, particularly roads and railways, belong to this damage sector. Sometimes also essential facilities such as hospitals, schools and fire brigades are considered in this sector; in other studies these are assigned to other sectors. Besides direct damage to the affected structures (i.e. costs for re- pair/replacement of damage facilities, equipment, etc.), dam- ages can occur due to a disruption of services, which have to be regarded as indirect damage (e.g. loss of revenue by the network operator, delay costs).

With regard to damage to infrastructure, only few data and no well-established models exist. Occasionally, models for assessing earthquake risk are adopted to estimate indirect flood damage (Dutta et al., 2003; Scawthron et al., 2006). Since damage is governed by many local factors, uncertainties are very high (Dutta et al., 2003). In the Multicoloured Manual (Penning-Rowsell et al., 2005) the examination of damage to infrastructure is mainly presented by case studies. Damage due to disruption of utilities is in general a function of i) the physical susceptibility of the flooded structures and networks, ii) the dependency of properties served by the affected utilities and networks, and iii) the ease of transfer- ability of production/service to a non-flooded site (redun- dancy). Penning-Rowsell et al. (2005) further recommend using the depth-damage approach for assessing direct damage. However, due to the site-specificity of utility works, no standard data are given in the Multicoloured Manual. Some are, however, included in the US HAZUS-MH Flood Dam- age Estimation Methodology for point facilities such as hos- pitals or for special components like bridges (Scawthorn et al., 2006). In contrast to other sectors direct damage to trans- portation infrastructure seems to be more influenced by flow velocity than by inundation depth (Kreibich et al., 2009). Consequently, effects by erosion and debris flow (closure of bridges) have to receive more attention. Further, standard costs for length units (e.g. km railway, km road) can be used as a basis for valuation.

Due to the variety of structures a three-step filtering process has been proposed with the goal to present a short list of assets for a detailed economic appraisal (Penning-Rowsell et al., 2005). This filtering consists of the following steps:

– enumerate relevant infrastructure assets at risk by assessing their sizes (e.g. length) and values (e.g. supply catchment, served population),

– assess the total risk for each infrastructure by roughly classifying the likelihood of damage and the scale of impact as high, medium or low,

– quantify (indirect) damages for "high risk" and "very high risk" assets only.

Similarly, in HAZUS-MH important lifeline components are selected for fragility modelling. Impacts to system functionality, relative cost of the component and the overall time to recover from damage are considered, as well (Scawthorn et al., 2006).

3.5.4 Agricultural sector

Flood damage in the agricultural sector includes losses of agriculture products, farm houses and farm infrastructure (Dutta et al., 2003). The reduction in yield and quality of agriculture products may require additional expenditures for sowing, tillage, and the application of fertiliser and crop protective agents. Additionally, damage to the soil might be relevant (Pivot et al., 2002). It refers to a potential decrease in the quality of soil due to pollutant deposition and a loss of soil structure due to compaction or erosion.

Total economic damages in the agricultural sector are frequently much lower than those in urban areas. Hence, dam- age evaluation is often neglected or only accounted for by using simple approaches and rough estimates (Fo¨ rster et al.,2008). For the estimation of building and infrastructure dam- ages commonly models from the residential and infrastructure sector are applied. Approaches for the estimation of agriculture product damages range from models which differentiate only between damage to arable land (crops) and grassland (e.g. LfUG, 2005; Hoes and Schuurmans, 2005) and others which differentiate between several crop types (e.g. Citeau, 2003; Dutta et al., 2003; Fo¨ rster et al., 2008). A significant difference to damage evaluations in other sec- tors is the importance of the time of occurrence of a flood with respect to crop growth stages and critical field operations (Penning-Rowsell et al., 2003). For example, flood- ing in July results in much higher damages for summer grain crops just prior to harvesting than flooding in August just after harvesting. In most models, time of occurrence is considered whereas the flood variables water depth, inundation duration, and flow velocities are only rarely taken into consideration (Table 8). Citeau (2003) gives a rough estimate of maximum tolerable submersion time, inundation depth and flow velocity for different rural land-use types. In order to obtain an estimate of the total expected damage, the estimated relative damage needs to be related to the market value that could have been obtained by the harvested crop without flooding.

4 Indirect economic damages

Indirect flood damages are induced by the direct impacts and transmitted through the economic system. Thus, for example, a production facility might be lacking an important input (electricity, raw materials, etc.) due to a flood event in its suppliers' areas, and thus be unable to operate thereby incur- ring financial loss. Indirect economic damage is necessarily attached to some form of interruption of usual business but strictly different from the business interruption caused by the direct physical impacts of flood water on production facilities. It is a secondary or trigger effect caused by the inter- linkages in the economic system (Cochrane, 2004). While recent studies on indirect economic damages – for example, Hallegate (2008) estimates the indirect damage of Hurricane Katrina in Louisiana at 28 billion US $ – demonstrate the eco- nomic importance of this category of damages, its measurement has not been undertaken to the same extent as for direct damages. This section identifies types of indirect damage and methods of measuring it, particularly existing modelling methodologies. It also describes ways in which vulnerability score cards can be employed to raise awareness in disaster management for indirect damages.

The magnitude of indirect damage is determined by the boundaries in space and time of the damage assessment. From a very broad temporal and spatial perspective, indirect economic damages of natural disasters are zero. Measured over the entire economy, the negative and positive indirect effects cancel out. For any reasonable boundary (city, state, catchment area, etc.), however, there will be net indirect effects from flooding. In the short-term, floods produce indirect economic damages from:

– Input/output losses to firms who are costumers (forward-linked) or suppliers (backward-linked) to the directly impacted businesses in the inundation area.

– Consumption reductions from the income and/or profit losses triggered by business interruption as a ripple effect, i.e. employees or private owners of the firms experiencing reduced production suffer income losses and subsequently cut their own spending.

Floods can also have long-term indirect impacts such as altered migration flows, relocation of industries, depressed housing values, and altered government expenditures that result from the new patterns of migration and regional development.

Evidence to date suggests that the indirect effects are more important in large disasters than in smaller disasters. For ex- ample, Hallegatte (2008) demonstrates that significant indirect economic damages for the state of Louisiana only arise

Table 8. Comparison of different damage functions for damage to crops.

Models (references)	Country	Development	Functions	Parameters
Citeau (2003)	France	synthetic	relative	Water depth, flood duration, flow velocity, submersion period, crop type
Neubert and Thiel (2004)	Germany	synthetic	relative	Submersion period
MEDIS-Model,	Germany	empirical-synthetic	relative	Flood duration,

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submersion period, crop type
Fo¨ rster et al. (2008)

LfUG (2005)	Germany	empirical-	relative	Specific

synthetic discharge

Dutta et al. (2003)	Japan	empirical	relative	Water depth, flood duration, submersion period, crop type
Hoes and Schuurmans (2005)	The Netherlands	synthetic	relative	Water depth

when direct damages exceed 50 billion US $. He also demonstrates that indirect impacts are larger if a natural disaster affects the economy during the expansion phase of its business cycle than if it touches it during a recession phase (Hallegatte et al., 2007).

Compared to direct effects, indirect damages are much more difficult to measure. Additionally, there are limited available sources of data for measuring indirect damages. Insurance data on business interruption are of limited value for that purpose, as most indirect effects, for example, power outage, do not qualify for compensation under business interruption insurance. Moreover, many firms do not carry business interruption insurance. The limitation of accessible primary data have led to attempts to measure indirect dam- ages using economic models of the type that have long been utilized for economic forecasting such as (1) Simultaneous equation econometric models, (2) Input-output models, and (3) Computable General Equilibrium models (Rose, 2004).

Studies evaluating model-based estimates suggest that the models developed for traditional economic forecasting tend to overstate indirect effects. Differences to observed impacts from post-event economic surveys are in the order of 70 to 85% (West, 1996). The reason for this overestimation of both, indirect regional economic damages from natural dis- asters and indirect regional economic gains from reconstruction, is that statistically based economic models have been designed primarily to forecast the effects of a lasting impact (e.g., an investment into a new commercial development). The historical interlinkages embodied in these models are likely to be substantially disturbed and temporarily changed during a flood. Dynamic adjustment features such as recovery, resiliency, interregional substitution, inventory adjustments, changes in labour supply, number of refugees, are not reflected in these models. In short, these models are inappropriate for simulating natural disasters; they must be substantially revised in order to produce reliable estimates of indirect effects. Computational algorithms modelling supply shocks, post-event supply constraints and time phased reconstruction in disaggregated spatial settings (van der Veen and Logtmei- jer, 2005; Yamano et al., 2007) seems promising to overcome this methodological gap.

Pfurtscheller and Schwarze (2010) develop a simplified vulnerability score card to raise awareness for indirect effects in regional disaster management. It considers vulnerability factors in a regional economy such as:

– Concentration of lost production in few (–) or many industrial sectors (+) of the regional economy.

– Constrained (+) or reserve production capacities (–), during an expansion (+) or recession phase (–) of the business cycle.

– Availability (–) or lack (+) of finance and reconstruction aid.

– High (–) or low (+) density of insurance for business interruption within a narrow (+) or broad (–) scope, the latter including indirect

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effects such as economic dam- age due to power outage.

Here, (–) signals a limited risk of indirect effects to the regional economy, whereas (+) indicates a considerable potential of indirect economic damage. The vulnerabilities could be measured along an A-B-C scale, for example, to be scored into an overall regional economic vulnerability index. A comparable, much more detailed and regionalised indicator set has been developed independently by Khazai et al. (2010).

5 Macro-economic damages

Macro-economic damage models study the effect of both, direct and indirect economic flood damages with regard to their effects on performance indicators of the national economy,

Table 9. Macro-economic indicators and expected effects.

Macro-economic indicator	Expected effects
Gross Domestic Product (GDP)	Growth loss in the occurrence year, accelerated growth in the following year (if not a end-of-year occurrence)
Balance of payments	Loss of exports and growing imports (balance of trade deficit) in the occurrence year, lesser imports in the subsequent year (due to decreasing income)
Net investment	Decrease in the capital stock (unplanned depreciation) in the occurrence year, investment in the subsequent in the following year
Inflation	Temporary price increase due to disruption and bottle-necks in supply
National debts	Lower tax income (decrease in private available income) and increased public spending

such as growth, balance of payments or net investment (Table 9). Since they reflect the national-level repercussions of direct damages *and* indirect losses, they must not be added to those effects. Macro-economic effects are a complementary view to assess direct damages and indirect damages from a national perspective. The most important macro-economic performance indicators and the expected macro-economic effects of floods and similar natural hazards on these indicators are given in Table 9, based on literature survey (Benson and Clay, 2000; Pelling, 2002; Mechler, 2003; ECLAC, 2003).

There is a large body of literature on the short- and medium-term GNP effects of natural hazards, mainly in developing countries (ECLAC, 2003; Mechler, 2003). The general findings are:

– There are no significant macro-economic effects in industrialised countries, but only regional and sectoral indirect economic effects.

– The effects of floods on national growth is short-term (years), but insignificant in the medium- and long- term (decades). Albala-Bertrand (1993) finds significant short-term effects only in 25% of his case studies of developing countries.

– An increase in national indebtedness and trade imbalances could be observed as a result of floodings in developing countries only.

– International comparative studies agree that macro- economic damages are mainly triggered by economic vulnerabilities (e.g. a low degree of diversification of production), and they are influenced by institutional factors such as the availability of government relief pro- grams or private insurance (empirically confirmed by Raschky, 2008).

– There are significant positive effects of national perfomance after natural disasters if international aid is provided.

6 Uncertainty of damage assessments

6.1 Availability and reliability of damage data

In comparison to other fields of water resources management, flood damage data are still scarce. Only a few data sets are publicly available and little is known about data quality. More efforts to collect flood damage data and the development of standardized methods have been constantly called for (e.g. Ramirez et al., 1988; Mileti, 1999; NRC, 1999; Yeo, 2002; WHO, 2002; Guha-Sapir and Below, 2002; Dilley et al., 2005; Handmer et al., 2005; Greenberg et al., 2007). The lack of reliable, consistent and comparable damage data is seen as a major obstacle for risk analyses and effective and long-term damage prevention (IFRCRCS, 1997; Changnon, 2003; Downton and Pielke, 2005). Many of the accessible data sets, such as EM-DAT (Centre for Research on the Epidemiology of Disasters – CRED, Brussels), contain dam- age data that have already been aggregated to a regional or national level. However, flood damage data are needed at a variety of spatial scales (national, regional, local, object scale) to analyze variations in damage and to investigate causal relations between the hazard characteristic and the amount of damage (Downton et al., 2005; Jonkman, 2005). Especially for the development of damage models, such as depth-damage curves, object-oriented data are needed. Such data sets are, however, hardly available or accessible. For Germany, recently the object-oriented flood dam- age database HOWAS 21 has been set up, containing already more than 5500 damage cases of four economic sectors (as in April 2010, http://nadine.helmholtz-eos.de/HOWAS21.html, in German).

There are many ways to measure the damages associated with a flood (Pielke, 2000), and accounting for all costs of disasters is complicated for different reasons (Downton and Pielke, 2005): first, indirect costs of disasters are difficult to measure and can often only be assessed by models (see Greenberg et al., 2007 for a review). Above all, disasters have direct and indirect benefits, e.g. infusion of disaster relief funds to affected regions, which should be crosschecked with the costs. Second, disaster damages are a function of the spatial and temporal scale that the analyst chooses in a particular analysis. Additionally, the to- tal amount of monetary damage depends on the purpose and context of data acquisition (e.g. loss adjustment by insurance or governmental relief fund) and the appropriate method for monetary assessment. Finally, many costs (and benefits) associated with a disaster are intangible. The true costs of disasters include hidden costs and benefits which are difficult to identify and quantify (Downton and Pielke, 2005).

In general, damage data are rarely gathered, (initial) re- pair cost estimates are uncertain and data are not updated systematically (Dowton and Pielke, 2005). Low standardization of the collection of flood damages might cause prob- lems with data quality with regard to accuracy and consistency (Wind et al., 1999; Gissing and Blong, 2004). For example, assessments of flood damage and flood characteristics (water level, velocity, etc.) at affected properties are in most instances based on subjective perceptions of building surveyors and may therefore be prone to variation (Nicholas et al., 2001; Soetanto and Proverbs, 2004). It is expected that damage estimates are more consistent and reliable if they are given by experienced surveyors or damage adjustors. How- ever, damage adjusters tend to be “generous” which may be a reflection of an allowance for intangible damages suffered by flood victims (Penning-Rowsell and Green, 2000). Thus, benchmarks of flood damage assessment should be developed which will also allow an assessment of possible re- pair strategies (Proverbs and Soetanto, 2004). As outlined by Dowton and Pielke (2005), there is a difference between initial damage estimates and the final/actual repair costs. That means that flood damage data collection must include regular updates of the costs and that a reference year for the costs has to be given.

Many observations illustrate these general remarks about damage data quality problems. For example, shortly after the severe flood event in Germany in August 2002 the total flood damage was estimated to more than 22 billion C. This amount was corrected to about 9 billion C in December 2002 Meanwhile, actual repair costs amount to a total sum of 11.6 billion C. A similar experience was made after other flood events, e.g. after the Great Mississippi Flood 1993 economic damage estimates differed by many billions of dollars (Changnon, 1996).

There are only few studies that analyze and compare flood damage data sets: Downton and Pielke (2005) and Pielke et al. (2002) analyze historical records of flood damage provided by the National Weather Service (NWS) in the USA, and compare them with estimates from other sources. Both analyses conclude that the accuracy of the damage data depends on the scale of the flood damage and/or on the scale of the aggregation. Damage data for small floods or local areas within a larger flooded area tend to be extremely in- accurate. Since there is no systematic under- or overestimation, positive and negative estimation errors tend to average out when estimates are highly aggregated, and hence, the accuracy increases with the aggregation over larger areas or longer time periods. For example, for damage in a state of less than 50 million US $ (in 1995 dollars) estimates from NWS and other sources often disagree by more than a factor of two (Pielke et al., 2002). For state damage above 500 million US $ the disagreement is smaller than 40%. Guha-Sapir and Below (2002) compare three global disaster data sets, namely NatCat (Munich Reinsurance Company, Munich), Sigma (Swiss Reinsurance Com- pany, Zurich) and EM-DAT (Centre for Research on the Epidemiology of Disasters – CRED, Brussels). Similarly, their analysis reveals a range of problems with damage data, such as lack of details, inconsistencies or data errors.

These examples illustrate the need to improve both, dam- age estimations and the quality of damage data since a good documentation and standardised collection and management of damage data are a prerequisite for the development of re- liable damage models. Some recommendations on how to improve data quality and how to standardize data collection are given in Queensland Government (2002), Downton and Pielke (2005), Thieken et al. (2009) and Elmer et al. (2010).

6.2 Sources of uncertainty in damage modelling

Damage modelling aims at predicting damages of potential future events or they are geared towards financial appraisals during and immediately after floods. In both cases damage models have to be transferred to another situation. These transfers can be grouped into (1) transfer between elements at risks, (2) transfer in time, (3) transfer in space, and (4) transfer in spatial scale. Each transfer is associated with uncertainty, in addition to the uncertainty and errors in damage data collection.

A large source of uncertainty in damage modelling is the enormous variability of damage between elements at risk (transfer between elements at risk). For instance, even two private houses of the same building type located next to each other are expected to experience large differences in their damage for the same flood event. Some of the flood characteristics, e.g. flow velocity, can dramatically vary with short distances. The same holds for other damage-influencing factors, such as contamination or the capability of the residents to perform damage-reducing measures. These influences are not predictable, or are – even with a large effort – only predictable to a small extent.

Transfer in time would not be problematic if the system under study was stationary. However, the vulnerability of elements at risk changes in time, and often at a high rate. Changes have to be expected in the asset values and in the susceptibility to floods. For example, Penning-Rowsell and Green (2000) point to technological changes which have led to increased susceptibility: modern retail and commercial outlets and industrial plants nowadays include electronic and computer-related equipment. This is usually valueless after being flooded, whereas its more robust predecessors could be repaired. Similarly, the increasing interconnectedness of modern societies and their dependence on infrastructures (energy supply, communication, transportation, water, etc.) produce new vulnerabilities, and sometimes unexpected second-order effects. Mitchell (2003) gives some examples of changing flood vulnerability in Europe, such as the increased use of floodplains by export-oriented businesses. The advantage of navigable waterways that connect deepwater international ports triggers increasing exposure to flood risks, as it is seen in the lower Rhine valley. Urban re- development projects in old river cities of northern Europe improve the attractiveness of waterfront areas. Low-value investments, such as old docks and crumbling warehouses, are substituted by higher-value investments, such as cultural facilities, shopping and entertainment complexes (Mitchell,2003). Johnson et al. (2007) report a substantial and above-inflation increase in the potential economic damages to residential, retail, commercial and industrial properties between 1990 and 2005 in England and Wales. Average economic damages to residential buildings due to the 2002 and 2005 flood events were more than twice as high as average economic damages due to flood events in 1985 and 1988 in the federal state of Bavaria, Germany (Thieken, 2008). Be- sides such rather long-term changes, changes acting on short time scales occur. The damages for the January 1995 flood in Cologne amounted to approximately 43% of the damages for the December 1993 flood, although the 1995 flood was slightly higher than the event 15 months earlier. Similar observations are reported for the adjacent catchment of the River Meuse (Wind et al., 1999). This dramatic reduction in damages seems to be a consequence of the increased awareness and capability of the affected people and of the administration in charge. Although temporal changes in vulnerability are frequently mentioned, they are usually not taken into account by damage models. As early as 1965, Kates proposed an adaptation option function (in addition to the damage function) that reflected adaptation of flood damage over time and space as result of training and improved information (Booysen et al., 1999). It has still to be proven if this idea, which is theoretically attractive, can be implemented in damage modelling, given the widespread lack of damage data. Currently, a regular updating of damage functions is done in UK.

Transfer in space of the relation between damage- influencing parameters and resulting economic damage is necessary since models are developed for certain spatial entities and have to be applied to other areas. For example, the model FLEMOps was derived from damage data of a severe flood event in 2002 in the Elbe and Danube catchments (Bu¨ chele et al., 2006; Thieken et al., 2008a). The question, whether a model is transferable to other regions or how the model should be adapted, has been investigated only rarely. An exception are FLEMOps model applications and validations in five Saxon municipalities that were affected by the flood in August 2002 in the Elbe catchment as well as in five municipalities in Baden-Wuerttemberg that experienced flooding in December 1993 in the Neckar catchment (Thieken et al.,2008a). While the mean relative error of the estimates for the Saxon municipalities amounted to 24% for FLEMOps+, it was more than 1000% in case of the municipalities in Baden-Wuerttemberg (Fig. 3), illustrating that transferability of damage models in space and time is limited (Thieken et al., 2008a). Transferability in space depends on the similarity – in terms of the relation between damage-influencing factors and economic damage – between the two areas. The authors are not aware of any investigation of regional similarity, based on objective methods. If enough data could be collected, the question of homogeneous damage regions could be investigated in quantitative terms, for instance similarly to homogeneous regions in terms of flood frequency (Hosking and Wallis, 1997).

Transfer in spatial scales occurs if a damage model has to be applied for another scale than the one for which it has been developed. Typically, damage models are based on micro-scale data, using damage data from single elements at risk. However, meso- and macro-scale damage assessments apply damage models for aggregations of elements at risk. We expect that this source of uncertainty is rather small compared to the other sources, if appropriate up-scaling and down-scaling approaches are used. For instance, micro-scale and meso-scale validations of the FLEMOps model revealed similar results (Thieken et al., 2008a). For one municipality in Saxony, Germany, Apel et al. (2009) showed that meso- scale approaches can even outperform more detailed models and provide a good compromise between data requirements, simulation efforts and accuracy of results.

6.3 Uncertainty and validation of damage modelling

Model validation aims at evaluating whether a model per- forms well in different (observed) situations and whether it can thus be used for predictions of unobserved situations. Frequently, the aim of damage model validation is to assess whether it is capable of reliably estimating the damage for a certain area (e.g., municipality, region) for a given flood event. Another objective of model validation is whether there are systematic estimation errors, e.g. whether damages at a given water level are always under- or overestimated. Such an evaluation is also relevant for parameters that are not (yet) included in the model, e.g. flow velocity. The out- come of a model validation could be to include further variables (such as flow velocity or flood duration) in the model. The more process-oriented model validation can primarily be performed on the micro-scale and requires detailed data (single objects with repair costs, input data for the damage model, further parameters).

One major shortcoming of damage modelling is that model validation is scarcely performed and that a quality assessment of damage estimates can thus hardly be achieved. The main reasons for this shortcoming are limited or missing observations and data. Owing to these data problems, validation methods that compare predicted damages against observations (absolute validation, Kirwan, 1997) are often not applicable in damage modelling. Ideally, actual damage data should be available for the complete spectrum of events that is of interest in a risk assessment. However, in most situations there are no damage data at all, or damage data are restricted to one or a few floods in the study area. Thieken et al. (2008a) compare estimates of the FLEMOps model for the residential sector to recorded repair costs. The model delivers very good results for the August 2002 flood in Ger- many. However, this model is based on damage data collected from the 2002 event, and application of the model to other floods in Germany shows much larger deviations (see above). Penning-Rowsell and Green (2000) tested synthetic damage functions of Penning-Rowsell and Chatterton (1977) against post-flood surveys by damage adjusters, and report general agreement between surveys and synthetic results.

If damage data of historical floods are not available and an absolute validation cannot be performed, other ways of assessing the plausibility or validity of the damage model should be sought. These include the use of expert knowl- edge, comparison of alternative damage models and methods for evaluating the process of model construction. The application of split sampling or cross-validation procedures may be further elements of validation, but require a comparatively large data base. An application is given in Kreibich and Thieken (2008).

Further, uncertainty and sensitivity analyses may be helpful when there are no damage data available for the area under study (Merz et al., 2008). If a model cannot be validated using observations, all hypothesis testing should explicitly consider the potential sources of uncertainty (Pap- penberger and Beven, 2006). This allows investigating important assumption, model inputs and processes. Thus, sensitive aspects of the damage modelling (e.g. Which assumptions dominate the result?) can be identified, and efforts can be guided for assembling further information and improving the modelling (e.g. What are the most valuable data for constraining uncertainty?). If the decisive elements of the damage modelling are reliable, then the resulting damage estimate is expected to be reliable as well, even if no observations are available. If the decisive elements are riddled with large uncertainty, then the damage estimate should be used with caution. A further benefit of uncertainty analyses is the additional information for the decision making process. On basis of an uncertainty analysis a decision different, most likely better, than the one taken without the knowledge about the uncertainty is possible (Merz et al., 2008).

There are only few studies that quantify the uncertainty of damage modelling. Using a damage database of approximately 4000 damage records of floods in Germany, Merz et al. (2004) quantify the uncertainty associated with damage modelling at the micro- and meso-scale. They show that uncertainty is particularly large for cases where only a small number of objects is flooded and for sectors with high variability, such as manufacturing. They also compare modelled damage at the level of rural communities for a 100-year flood in 1993 in southwest Germany with reported damage. This comparison illustrates the considerable uncertainty and bias, in terms of under- or overestimation, that is associated with damage modelling. Further, it shows the benefit of evaluating simulated damage values with reported data.

Egorova et al. (2008) incorporate uncertainty into the standard method for predicting flood damage in the Netherlands. Uncertainty is introduced into damage modelling by applying a probability density function to the maximum damage per unit object and to parameters of the relative damage function. They investigate the spatial dependence of damage be- tween neighbouring flooded model cells. If one cell has a certain damage susceptibility, then the probability is high that a neighbouring cell has a similar susceptibility, e.g. due to similar flood experience. However, the dependence is unknown, and Egorova et al. (2008) apply three different dependence models (independence, complete dependence, partially dependent) to assess the influence of the dependence structure. Interestingly, the uncertainty in the total damage of three flood scenarios of a dike ring in Central Holland is relatively small. The authors explain this result by the small uncertainty of the maximum damage per unit object. It would be interesting to see how the damage estimates and their uncertainty compare to actual damage data.

An interesting question which has been hardly explored is the relative contribution of the different elements of a flood risk analysis to the total uncertainty. Merz and Thieken (2009) perform a risk analysis, consisting of three modules: (1) flood frequency analysis, (2) inundation estimation, and (3) damage estimation. They estimate the relative contribution of each module and find that it varies with the return period of the considered floods. The contribution of the damage modelling is low compared to the two other sources of uncertainty. This result can, however, not be generalised. The magnitude of the uncertainty depends on many aspects, such as the amount and quality of information for a certain module, the adequacy of the models used or the number of uncertainty sources that are included in the analysis.

CONCLUSION

The estimation of economic flood damage is gaining greater importance as risk management is becoming the dominant approach of flood control policies throughout Europe (European Commission, 2007). In times of scarce public resources and in the face of an increased vulnerability it becomes an essential element of the optimization of flood mitigation measures and for the assessment of flood susceptibility. Given these challenges, the available methods are far from being satisfying. So far, simple approaches dominate, mainly due to limitations in available data and knowledge on damage mechanisms. The results of damage assessments depend on many assumptions, e.g. the selection of spatial and temporal boundaries, and there are many pitfalls in economic evaluation, e.g. the choice between replacement costs or depreciated values.

The assessment of direct economic damages can be divided into three steps, each having potential for improvement. The classification of elements at risk is mostly based on economic sectors with different detail concerning sub- classes within a certain sector. These classifications describe only a rather limited share of the variability that is observed in damage data. Moreover, they are not based on objective and/or statistical classification methods. Expert knowledge and conditions of the damage assessment currently determine the details of classification and the actual derivation of class boundaries. A future research direction is the development of classification schemes which are less subjective. Further, it should be investigated under which conditions classification schemes are advantageous which are more oriented towards damage mechanisms. An open question in the classification step is the use of sectoral versus object-specific approaches. A single large industrial plant can incur direct damage that exceeds that of nearby dwellings and other commercial operations by orders of magnitude. Such large variability in industrial damages might suggest the use of synthetic damage functions, using questionnaires or expert opinions for the individual assessment of damage potentials at every industrial plant. However, this approach is not feasible for damage assessments in large areas. Besides, it has been shown that uncertainty in damage modelling decreases with increasing areas and numbers of affected objects, since outliers lose their importance (Merz et al., 2004). A problem-oriented combination of empirical and synthetic data and models seems to be most suitable in many damage assessments. How- ever, studies are necessary which investigate the variability among elements at risk and from which recommendations can be drawn on the adequate approach and detail of classification. At larger scales, e.g. for complete countries, there is a trend towards “standardization”. Standardized methods or governmental recommendations are given in several countries, e.g. in the Netherlands (Egorova et al., 2008) and the UK (MAFF, 2000). Given the current lack of reliable data on flood damages and their influencing factors, we believe that standardization is a useful path. However, this should not impede research for improved knowledge about damage mechanisms.

The second step in the assessment of direct economic damages is the quantification of the exposed asset values. Our review shows the methods currently in use vary considerably in terms of detail concerning the stratification in economic classes and the spatial disaggregation of areal values. Often crude approaches are chosen. They may be adequate for applications where gross estimates suffice. However, they may be too crude for other applications due to their negligence of important characteristics such as differences in building types. Compared to the resolution and detailedness of flood hazard modelling, even the most detailed asset assessments are regarded as coarse, often leading to a spatial mismatch between hazard and exposure data. In order to overcome this mismatch, disaggregation needs greater attention.

Due to the large variety of approaches found for describing susceptibility, the third step of direct economic dam- age assessment, we have limited our review on a few important sectors. Despite considerable heterogeneity among susceptibility models, they have in common that complex processes, i.e. damage mechanisms, are described by simple approaches, e.g. depth-damage curve. Most of the damage-influencing factors are neglected in damage modelling, since they are very heterogeneous in space and time, difficult to predict, and there is limited information on their (quantitative) effects. More sophisticated methods, e.g. multi-variate analyses and exercises in data-mining, should be applied for identifying patterns in damage data and for correctly attributing damage-influencing factors to observed damage. It has been shown that factors, such as contamination of flood water or the capability of residents to perform damage-reducing measures, have the potential to significantly affect flood damages. Although these influences may not – or only to a small extent – be predictable, it is necessary to understand which factors are dominant under which conditions.

In summary, there seems to be a mismatch between the high relevance of damage assessments and the quality of the available models and datasets. This statement is even more valid for indirect damages. They are important specifically in large disasters but difficult to assess with the current methods in use. Models developed for traditional economic fore-casting tend to greatly overstate the indirect effects. Explicitly modelling supply shocks, considering post-event supply constraints and time phased reconstruction in spatial settings could overcome this methodological gap. Simplified qualitative methods such as risk score cards are able to raise awareness for indirect effects in flood risk management.

Given this premature state of economic flood damage assessment, aspects of data availability and model reliability are very important. However, most available data are heterogeneous, low quality and often non-validated. Consequently, empirical damage functions are unreliable and can be misleading. The lack of reliable, consistent and comparable damage data is seen as a major obstacle for sound risk assessments. Much larger efforts are required for (empirical and synthetic) data collection and for providing homogenous, reliable data to scientists and practitioners. In particular, efforts should be intensified for heterogeneous sectors with a high damage potential like industry and infrastructure. At the same time, quality proofing and validating damage assessments need to be intensified before we arrive at a set of sound and useful data and models within Europe.

Besides the large variability in terms of damage between elements at risk, two dominant sources of uncertainty in damage modelling are transfer in time and transfer in space. Spatial and temporal differences in asset values and in susceptibility are significant, so that damage models are difficult to transfer between regions or between points in time. This problem has not received enough attention. It is an open question, to which extent damage models can be transferred from one region to another and from one flood to another event. These uncertainties can only be reduced by larger investments in the understanding of the dominant drivers of changes in damage variability, and by systematic analyses of the spatial and temporal changes in asset values and susceptibility. A major shortcoming of damage modelling is that model validation is scarcely performed. On the one hand, this is understandable in view of data scarcity. On the other hand, progress in damage modelling can only be expected if every possibility is used in order to evaluate model results against observations and to assess model plausibility against any other evidence. Uncertainty analyses and thorough scrutiny of model inputs and assumptions should be mandatory for each damage model development and application, respectively.

In our view, flood risk assessments often invest much more in the hazard assessment part. Damage assessment is frequently seen as some kind of appendix within the risk analysis. Given the importance of damage assessments, a more balanced viewpoint between hazard and damage assessment seems warranted. This holds also true for other natural hazards. In fact, flood damage modelling is quite advanced in comparison to damage assessments for avalanches, storms or droughts. Thus, advances in flood damage assessment could trigger subsequent methodological improvements in other natural hazard areas with comparable time-space properties such as windstorms, but will need substantial conceptual modifications for natural hazards with different time-space properties that are better framed as man-nature-interactions such as droughts and forest fires.

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