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Contents

Abstract

Globally, floods are the most damaging type of disaster. One important tool to efficiently address flood risk is the residential flood damage function, which measures the vulnerability of assets to one or several factors linked to flood events. Damage functions have been the subject of research for more than 50 years. However, their ability to estimate actual flood damage is still highly uncertain. This study assesses the development and use of flood damage functions, and identifies key issues to improve their use in policy decision making. Literature on flood damage functions has been extensively assessed via a systematic search of peer-reviewed literature in the database ISI Web of Science. Moreover, a hand search has been performed to include key published studies in relevant journals or by relevant authors. Grey literature has also been identified and included when it contains valuable information. The results of this study indicate that the extent of asset damage due to flood depends on several factors such as water depth, flow velocity, duration, pollution level, building features, time of occurrence, warning, previous experience, and private precautions, among many others. As expected, we found that multifactorial models perform much better than single factor models in predicting damages, but they are rarely used. The depth-damage relationship is the most used function in both research and practical applications, which is found to have a low predictive capacity of actual flood damage. Additionally, the choice of asset value and its effect on risk assessment are rarely addressed in the literature. Results also indicate that several key issues should be considered when using damage functions as guidance for policy choices, in particular: transferability of functions among different contexts and from developed to developing countries, equity between low and high-income areas when using a damage function to estimate the benefits of mitigation, and transparency of underlying assumptions and uncertainties in model results. The flood damage function is an important part of the flood risk equation that is increasingly used to guide policy and investment choices on flood risk reduction. As this research shows, analysts should be informed about the implications of their choice of damage function, including its underlying assumptions, validity and reliability, as well as the implications for equity and transferability.

Acknowledgement

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About the Author

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Introduction

Floods are the most common natural hazard in the world (Gupha-Sapir et al. 2014). It is the natural disaster that affects most people, leads to the greatest loss of life, destroys the most homes, and causes the largest monetary impacts of all natural disasters (EM-DAT 2016). Climate change will increase the frequency and severity of extreme events including floods, while also exposing more people and increasing their vulnerability (IPCC 2012, Thieken et al. 2016). Global climate change will affect flood risk, but since flood risk reduction is often approached at watershed scale, local climate change effects and land use effects (and land use planning) are more important than global climate change prediction when adapting to future scenarios (Whitfield 2012).

The Residential Flood Damage Function (RFDF) is a crucial input to quantitative flood risk assessment. Reliable RFDFs are essential for flood loss estimation (Elmer et al. 2010a, Gerl et al., 2014, Tate et al., 2015, Yang et al. 2015), and hence also to quantitative flood risk assessment and policy formulation. It has been showed that RFDFs are the most important component in an economic analysis of flood risk reduction (USACE 1992). An increasing focus on economic efficiency of flood risk reduction has also increased the demand for quantitative risk assessment models as input to economic analysis (Jongman et al., 2012).

The extent of flood damage depends upon a multitude of factors such as water depth, flow velocity, duration, pollution level, building features, time of occurrence, warning, previous experience, and private precautions, among many others (Boettle et al. 2011, Elmer et al., 2010, Messner et al. 2007, Middelmann-Fernandes, 2010, Thieken et al. 2005). RFDFs are used to estimate the vulnerability of assets in relation to one or several of the damage influencing variables (Meyer et al., 2013b). Despite the fact that several studies show that the extent of flood damage relies upon multiple factors, the usual approach is to estimate damage only with respect to water level (Thieken et al. 2016).

There are countless damage functions available through consultant agencies, governmental agencies or in academia for use in the developed world to estimate benefits of flood mitigation in terms of avoided damage costs. Interpretation and application of damage function estimates require insights into the purpose for which they are derived (Meyer et al. 2014). Although RFDFs are internationally accepted, there are relatively few published studies that give detailed information of the methodology of their construction (Smith 1994). Flood damage modeling has not received much scientific attention and the theoretical foundation of damage models should be further improved (Kelman & Spence 2004, Wind et al. 1999, Ramirez et al 1988). The objective of this study is to present a review of available RFDFs, their development, and role in policy formulation. Moreover, the study highlights critical aspects and implications of the use of damage functions in flood risk assessment and management, specifically validity, transferability, equity, and transparency.

Flood risk assessment for public policy

Accurate disaster loss data and sound estimates are needed by policy makers for decisions about disaster assistance, investment in risk reduction, policy evaluation, and scientific research priorities (Downton et al. 2005). Economic analysis of flood hazard risk reduction is complex but is an essential tool to guide policy makers, providing important rationale and information in the decision making process (Jonkman et al. 2004). In such economic risk assessments, the actual probabilities of flood occurrence need to be taken into account. This can be done using probabilistic risk assessment approaches where the damage function estimates the damages inflicted upon assets (the dependent variable) by flood water. Quantitative (probabilistic) risk (R) is usually described as a function of the probability of a hazard (P) and the consequences of that hazard (C), $R = P \times C$. Where the consequences are the product of the exposure of objects to hazards, and the vulnerability of objects when exposed, $C = E \times V$. The majority of flood risk analyses take a technical approach focusing on the first part of the function, the hazard probability (P). Potential consequences (C) have not attained the same scientific interest despite the obvious impact they have on the outcome of risk estimation (R). The concept of the flood damage function has, however, become an umbrella term for functions expressing extent of flood damage. What they estimate, their level of detail and how they are derived depends on the purpose of their application. It is important to be aware of the significant differences between the various types of functions, despite their common denomination.

Damage functions can be applied both in ex-post and ex-ante analysis (Tate et al. 2015). In ex-post analysis, they can be a tool to quickly allocate resources for assistance in the recovery and rebuilding phases after disasters (Meyer et al. 2014, Tate et al. 2015). They can cover different spatial scales, from the micro level to supra-national. At the supra-national level, they can be used to identify and compare risk related to cross-border river basins, and thereby serve as input to compensation allocation by solidarity funds such as the EU solidarity fund (Jongman et al. 2012). Global, pan-European, supra-national or national flood damage functions can also be used to measure effects of different time variant risk factors upon flood damage, such as climate change and socio-economic growth (Mechler & Bouwer 2015, Barredo 2009), and use these effects to communicate changes in risk over time to stakeholders.

Most often, however, flood damage functions are used in ex-ante analysis to estimate the benefits of flood risk reduction and to evaluate the economic feasibility of implementing actions to decrease flood damage (Meyer et al., 2014, Tate et al., 2015). Used in this way, flood damage functions estimate benefits of risk reduction in terms of damages avoided in future flood events. These functions represent the vulnerability of elements when exposed to flooding and help identify the most effective way of reducing those vulnerabilities. They thereby serve as justification to spend (or not to spend) public resources in risk-reducing projects. They can also serve as input to decisions regarding which areas to protect or not (Messner et al. 2007).

Estimating flood losses for risk reduction planning is an increasingly important aspect of flood risk management (Tate et al. 2015). Cost information influences the formulation of flood policy including the allocation of funding, regulations and plans aimed at reducing flood risk (Middelmann-Fernandes 2010). State-of-the-art cost assessments are, however, far from delivering comprehensive and precise monetary estimates (Meyer et al. 2013), and expected damage can vary greatly depending on choice of damage function which can make the difference whether or not a project is economically feasible.

Table 1. Categorization of flood damage.

	Tangible	Intangible
Direct	**Physical damage to assets:** **Buildings** **Contents** **Infrastructure**	**Loss of life** **Health effects** **Loss of ecological goods**
Indirect	**Loss of industrial production** **Traffic disruption** **Emergency costs**	**Inconvenience of post-flood recovery** **Increased vulnerability of survivors**

Source: Floodsite (2016).

Flood damage

Damage can be inflicted directly or indirectly on objects exposed to flooding and can be further characterized as tangible or intangible damage. Direct tangible damages are physical damage to objects. These damages can be considered to be the most "visible" economic consequence. It is caused by physical contact of flood water with property or other objects, which leads to destruction of elements or reduction of their functionality. Intangible or indirect damages occur following the actual event and affect a wider area in space and time than what directly involved in a hazard zone (Kreibich and Thieken, 2008).

There are several ways on categorizing flood damage. The most common way of categorization was first suggested by Parker et al. (1987) and later adopted widely within the flood risk management community. Examples of damage categorization are presented in Table 1. Another very similar categorization is presented in Meyer et al. (2013). It categories flood damage into cost-categories. It is based on Parker et al. (1987) but considers business interruption cost as a separate sub-category since these costs are suspected to require different cost assessment methods than other indirect damages. It further includes risk mitigation costs in the framework. The categorization approach in Meyer et al. (2013)

therefore results in five cost categories; direct costs, business interruption costs, indirect costs, intangible costs and risk mitigation costs.

Estimating the benefits of flood risk reduction entails evaluating the damage that would incur if no actions were taken (Rose 2009). The optimal scenario would be to include all cost and benefits related to a set of appropriate risk-reducing projects, and then choose the project which delivers the highest benefit-cost ratio (assuming that this project achieves the estimated risk reduction and assuming that the distribution of the costs and benefits is considered acceptable). Most commonly, however, the only flood impact taken into account in quantitative risk assessments is damage to residential property (Tate et al. 2014, Meyer et al. 2013, Smith and Ward 1998). Damage to residential areas therefore very much influences estimation of the benefits related to risk reduction measures. The most frequently used approach to estimate this direct tangible damage is by utilizing a RFDF that expresses the cost of flood damage inflicted upon an object as a function of one or more damage inducing factors (Meyer et al. 2013).

The residential flood damage function (RFDF)

The application of RFDFs has long been accepted as the standard approach to benefit estimation in economic analysis of risk reduction investments. RFDFs represent the vulnerability of objects when exposed to flooding and are needed to provide information on the susceptibility of elements at risk against flood characteristics (Messner et al. 2007). An RFDF can be developed to estimate damage at object level or at an aggregated level representing homogenous residential areas (Messner et al. 2007). RFDFs are also referred to as stage-damage functions, depth damage functions, vulnerability functions, susceptibility functions, or loss functions (Jongman et al. 2012, Meyer et al. 2013, Elmer et al. 2010a, Kreibich and Thieken 2008, Messner et al. 2007, Smith 1994, Thieken et al. 2006).

There are a few basic assumptions that apply to RFDFs independent of how or when they are derived: 1) Depth-damage relationships are based on the assumption that water height and its relation to structure height is the most important variable in determining expected value of damage to buildings (USACE 1992, Penning-Rowsell and Chatterton 1977); 2) Similar structures/properties, when exposed to the same flood characteristics and water depths, can be assumed to experience damages of similar magnitude or proportion to actual values (USACE 1992, Penning-Rowsell and Chatterton 1977); 3) Asset values are to be represented by depreciated values of the structures and content (Messner et al. 2007, USACE 1992, Penning-Rowsell and Chatterton 1977). How asset values are actually assigned differ somewhat between studies. In Bubeck et al. (2011), some of the models apply depreciated asset values while other models apply replacement cost. When deriving the Flemish functions (Belgium) for residential damage, market values were used (de Moel and Aerts 2011). Often the assignment of asset values is not specified.

RFDFs can express damage in monetary absolute units, or in relative terms as an index or percentage of total value (Messner et al. 2007, Meyer et al. 2010). The absolute functions and the relative functions therefore differ in the way they integrate monetary values into the damage calculation. The absolute RFDFs express damage in absolute values relating each water depth to an absolute monetary value. Absolute RFDFs are considered by USACE (1992) to be useful only when applied to particular buildings at one point in time. Since the relative RFDFs express damage as a percentage of asset values, such as structure damage as a percentage of structure value and contents as a percentage of contents value, for each level of water, this approach requires that the total value of the assets at risk within an area to be assessed. The standard depth-damage relationship applied to residential property often incorporates a structure to content relationship (USACE 1992). For residential property, US Army Corps of Engineers applies a ratio of 25-50 percent of structure value (USACE 1992). The principal assumption is that content value increases with household income, except for very poor households.

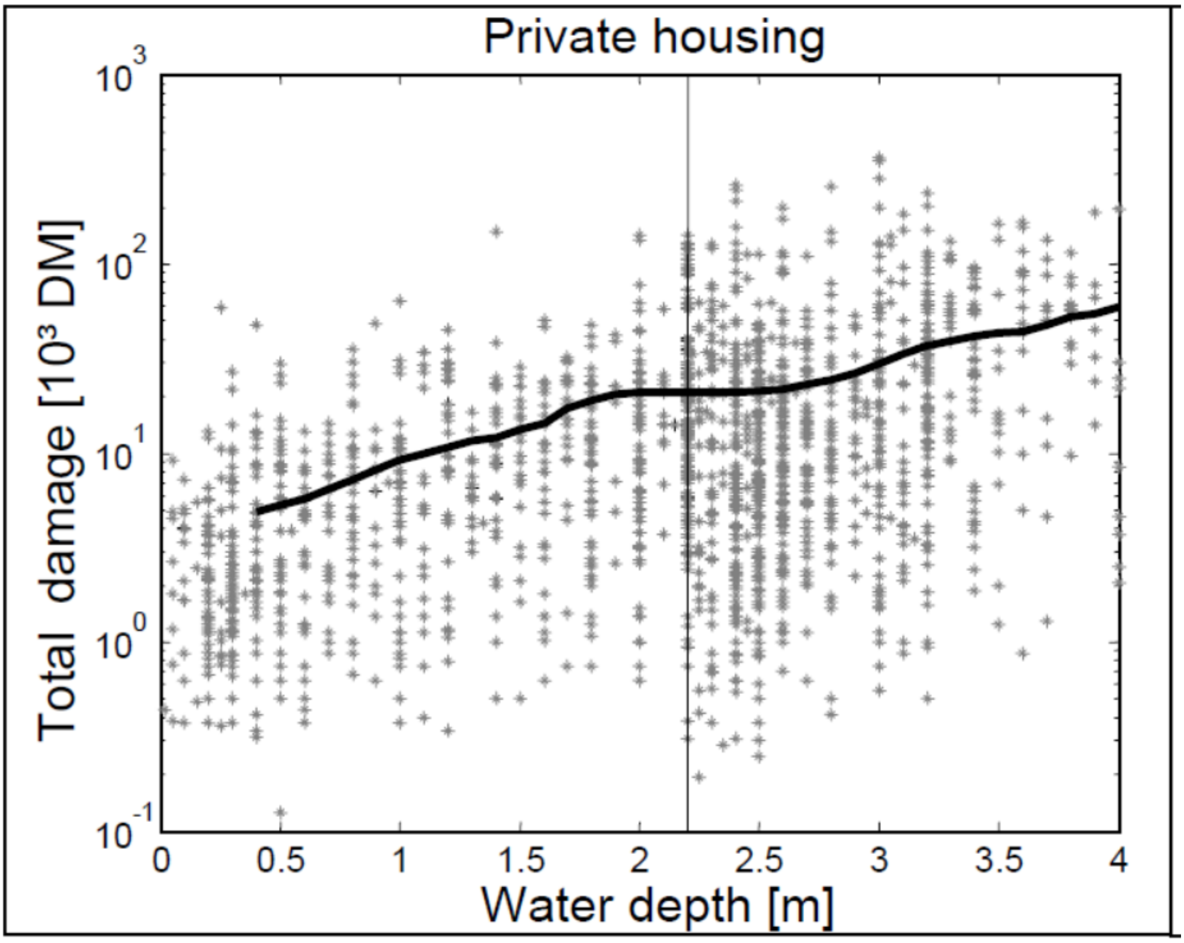

Figure 1: Example of an empirically derived DF based on 9 flood events in Germany between the years 1978-1994. The figure reflects the large variation of damage observation around the estimated line (RFDF). Source: Merz et al. 2004.

RFDF can be derived using empirical or synthetic approaches. Empirical RFDFs are based on observed flood damage data or post-flood survey data on affected properties, the type of each property, flood characteristics and extent of damage, gathered after flood events

(Messner et al. 2007). Post-flood survey is, however, time-consuming and expensive and depends on the actual occurrence of floods. The RFDFs are usually derived from the empirical data using regression analysis. This is seen as the best method of measuring the effect of different damage influencing variables since it can measure the strength of the relationship between damage and several variables, and the strength of the model itself (Messner et al. 2007, USACE 1992). However, there have been problems obtaining reliable estimates of important variables using regression analysis and the damage variation explained by regressions is usually low (USACE 1992). Due to the low explanatory capacity, RFDFs derived using regression approaches are seen as not being useful for predictive purposes (Smith 1994, Penning-Rowsell and Chatterton 1979, Grigg and Helweg 1975). Furthermore, the regression approach requires a large sample size as the whole variety of different types of building structures and building material must be represented (Messner et al. 2007). The approach was long, however, seen as the most correct approach to derive damage functions, and is still in use (for example in Germany). Figure 1 presents an example of an empirically derived RFDF.

In contrast to empirical RFDFs, synthetic functions are constructed based on hypothetical levels of flooding. Typical structures and quantity of contents are used to analyze what would be the damage at different flood levels. The value of the components is assessed and susceptibility of each of these items is estimated by expert judgment (Messner et al. 2007). The major advantage of the synthetic approach is that it does not require the occurrence of a flood. The method is generally quicker and less expensive than post-flood surveys (UASCE 1992). A disadvantage is the hypothetical nature of the functions. The approach requires good skilled analysts, and an understanding of specific flood circumstances and how it will affect buildings. Since the synthetic stage-damage functions are derived independently of the flood experience, they provide a set of internally consistent estimates under conservative economic assumptions (UASCE 1992). An example of synthetically derived RFDF can be found in Figure 3. Despite the methodological differences between empiric and synthetic approaches, the approaches can also be mixed, for example, the default depth-damage curve in the Hazus flood model is developed based on expert opinion, historical damage data, and numerical modeling (FEMA 2016, Nastev and Todorov 2013).

Method

Literature on flood damage functions was extensively assessed based on a systematic search of peer-reviewed literature in the database ISI Web of Science. Moreover, a hand search was conducted to include key published studies in relevant journals or by relevant authors. Grey literature was also identified and included when it contained valuable information.

Search expression used in ISI web of Science:

- Flood AND ("damage function*" OR "stage damage function*" OR "vulnerability function*" OR "susceptibility function*" OR "loss function*")
- Hazus OR Flemops OR Howas OR Anuflood

In total, almost 100 relevant publications were identified. Mostly peer reviewed journal articles but also books, governmental reports, dissertations and manuals. 60 of these are represented in this study.

Results

The past and the present: how did the RFDF become so important to flood risk assessment?

Standardized flood damage functions, as a uniform approach to flood damage estimation (project benefit estimation) was first outlined by Gilbert White in 1945 (Smith 1994). The first application of standardized flood damage functions to buildings was in the USA for use associated with the National Flood Insurance Act (1968) (Smith 1994). The Flood Insurance Act attached great importance to the cost efficiency of mitigation projects (FEMA 1968). With the implementation of the Act, the need for a tool/guidance to estimate benefits of mitigation measures were requested, especially by consulting engineers and federal agencies (Grigg and Helweg 1975). Documentation and compilation of flood damage data have, however, been standard procedure prior to this. The Weather Bureau started documenting impacts of floods in the US in 1902. The application of economic principles had already been greatly accelerated by the Flood Control Act of 1936 (Kates 1965). Much effort was put into developing flood damage functions in the US for both residential and commercial flood impact estimations to satisfy the requirement of an efficiency evaluation prior to spending public resources in mitigation projects.

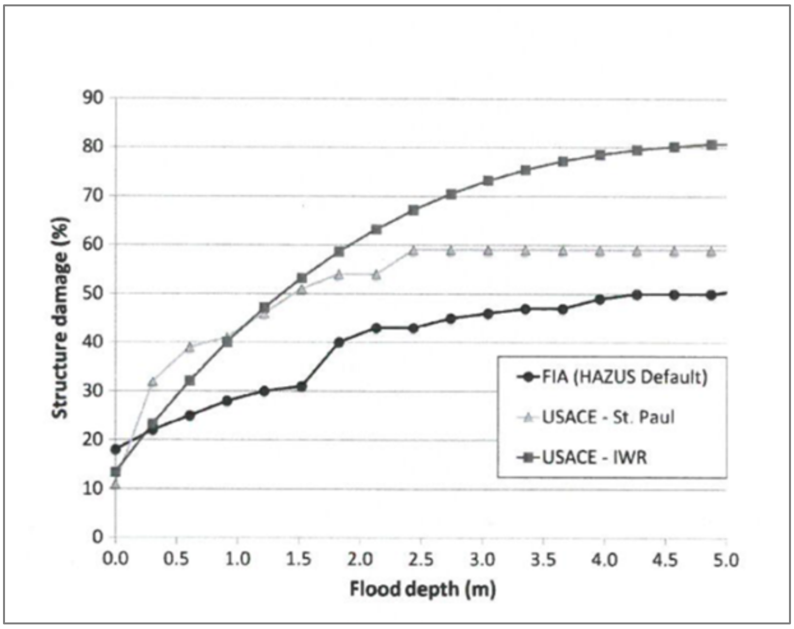

Figure 2: Examples of HAZUS depth damage functions for one story, single family home without basement, including default function. Three of the 900 DF's within the Hazus flood model (Tate et al. 2015).

Earlier, the basis for project implementation weighed heavily on experiences from past floods. By assuming a depth-damage relationship, flood damage could be derived as a function of water level (White 1945, Kates 1965). Regression analysis was used to estimate the effect of flood water upon flood damage. Water depths/levels could, however, only explain a very small part of the variation in damages and therefore did not do a very good job of supporting the basic assumption of the depth-damage relationship. A synthetic approach to damage functions were suggested by White (1964) and further developed by Kates (1965). The synthetic approach was to circumvent the inadequacy of empiric RFDFs by modeling the depth-damage relationship based on "expert knowledge" and "What if" scenarios (Kates 1965, White 1964). Generalized depth-damage relationships were established for several types of residential buildings in the US in the beginning of the 70's (USACE 1992). The US RFDFs have been continuously updated, improved and further standardized and are available in the software package, HAZUS provided by the Federal Emergency Management Agency (FEMA). Several hundred RFDFs have now been developed and added to HAZUS, derived from claims data and engineering analyses. These serve as a benchmark in catastrophe modeling, both in academia and industry. HAZUS assumes inclusion of replacement costs for buildings but this is not always applied because of the unavailability of such data (Cummings et al. 2012). The default RFDF in HAZUS, together with two other Hazus RFDFs, are displayed in Figure 2. The reliability of the economic estimates from the modeling process is, however, not well understood (Tate et al., 2015).

Parallel to the rapid development of the US RFDFs in the 70's, interest in quantifying flood damages and the need to make efficient decisions also became apparent outside the US. During the 70's, a set of synthetic stage damage functions were produced by the Middlesex Flood Hazard Research Center, inspired by the US approach, and published in the Blue Manual by Penning-Rowsell and Chatterton (1977) (later updates in 1987, 1992, 2005, and 2013). Prior to this, effort was also made in the UK to empirically derive RFDF functions. The results of these efforts were considered to have little predictive value (Penning-Rowsell and Chatterton 1977). After the massive effort of Penning-Rowsell and Chatterton (1977), we found no information on effort to pursue/derive empirical damage functions in the UK. However, the UK functions are still seen as the most comprehensive set of damage functions in Europe (Jongman et al., 2012, Merz et al. 2004).

Parallel to the process in the US and UK, effort was also made in Australia to standardize flood damage estimation (Smith 1994). As in the US, they first based their flood damage estimation on experiences from actual events using 400 events that occurred due to the Brisbane flood in 1974. The Australian regression analysis gave the same indication as empirical analysis in US and UK, depth could explain only a very small part of the variation in flood damages.

After the great floods in central Europe in the mid 90's and early 2000's, substantial effort was made in several European countries to compile and estimate flood damages. A German research group at the Helmholtz-Zentrum in Potsdam has invested considerable effort to derive damage function based on observed flood impacts and might be the source of the most comprehensive purely empiric data sets. Germany probably has the most comprehensive set of empirical damage functions resting upon actual data and survey data collected in the aftermath of floods. Despite this fact, Elmer et al. (2010) emphasize that a database with reliable, comparable, comprehensive, consistent and up-to-date data do not exist in Germany. Other European countries also developed their own sets of functions such as Netherlands and Czech Republic, while other countries such as Canada, South-Africa have adopted function developed in the US or UK. At present, there is an extensive amount of damage functions available from consultant agencies, governmental agencies or used in academia.

Damage influencing variables and multifactorial models

Damage influencing variables (vulnerability factors) can be divided into impact factors and resistance factors (Penning-Rowsell and Chatterton 1977). Flood damage are said to be influenced by: depth (in-stream water levels or land-based inundation depth), volume, flow velocity, duration of flood, time of occurrence, water quality, sediment or debris load, contamination (chemicals), building construction, age and materials, precaution, early warning, lead time and information content of flood warning, previous experience with flooding, quality of public response in a flood situation (Boettle et al., 201, Green et al. 2006, Komolafe et al. 2015, Messner et al. 2007, Merz et al. 2004, Middelmann-Fernandes 2010, Thieken et al. 2004, Yang et al. 2015). A challenge in damage loss modeling is to identify how and to what degree impact and resistance factors influence the damages (Elmer et al. 2010). Different types of floods, such as riverine floods, flash floods, storm surges, slowly rising lake floods or inundation due to levee breaches or groundwater rise, probably cause different kinds and extent of flood damages. Therefore, analyzing how and to what extent different flood characteristics impact buildings are highly relevant.

Table 2. List of damage influencing variables.

Impact factors	Resistance factors
Water depth	Building construction
Volume	Building age
Flow velocity	Building material
Flood duration	Early warning
Time of occurrence	Quality of warning
Water quality	Preparedness
Sediment or debris load	Previous experience
Contamination (chemicals)	Private precautionary measures
	Quality of public response

Merz et al. (2004) analyzed a dataset representing nine different floods in Germany between 1978 and 1994. They found that water depths alone, poorly explain the variability in damage to buildings. The reason is that flood damages are determined by various factors besides water depth. Thieken et al. (2005 and 2007) analyzed survey data collected in the aftermath of the 2002 flood in Germany. Thieken et al. (2007) found that in areas prone to flash floods it is important to consider the damage influencing variable; flow velocity, as well as water depth. Further, in regions affected by levee braches the damage influencing variables contamination and duration had significant effects, despite being exposed to moderate water levels. Overall, however, water level and contamination showed higher correlation with building and content damage than flow velocities and flood duration (Thieken et al. 2007).

Thieken et al. (2005) found that water level, flood duration, and contamination of the water are the most influential factors for building and content damage, but also that building characteristics, in this case building size, and the building value are of importance for the extent of flood damage. Furthermore, the study also showed that private precautionary measures are able to reduce flood losses, but official flood warning and emergency measures have less influence. Socioeconomic variables and flow velocity found to have only small effects upon extent of flood damage (Thieken et al. 2005).

Elmer et al. (2010) analyzed the correlation between flood characteristic and flood damage using 2158 damages to residential buildings occurring in Germany in 2002, 2005, and 2006. They found a highly significant positive correlation between extent of damage and recurrence interval, regardless of actual water level, and that recurrence interval could not be substituted by any other damage influencing factor. Grahn and Nyberg (2014) analyzed observed damage due to slow rising lake water levels and found that flood characteristics such as depth and duration, buildings characteristics such as structure and age, and private precautionary measures affect the extent of flood damage.

The damage influencing variables reviewed in this study are divided into impact factors and resistance factors and are listed in Table 2. Despite the agreement on the multifactorial aspect of flood damage, the literature within this area is scarce, not very nuanced, and the impacts the different damage influencing variables have upon the extent of damage are not well understood. A few multifactorial models exists, but more effort should be put into consideration of damage influencing factors so that RFDFs can be developed to include these factors on regular basis in flood risk assessment.

Multifactorial RFDF

Penning-Rowsell et al. (2013) take flood warning into account but express this variable with a curve representing lower vulnerability when warning time is given, and cannot really be called a multifactorial model (Figure 3). Dale et al. (2004) have developed Velocity-stage-damage functions for Australian residential buildings (Middelmann-Fernandes 2010). The functions do not account for water depth so the model is still a single parameter model. In addition, the functions only represent the buildings that, because of flooding, get destroyed when moving off their foundation, and need to be combined with other functions (for example depth damage function) to include other residential flood damages.

Some multifactorial functions exist in the literature that account for more than one damage influencing variable e.g. FLEMOps considers water level, building, type and building quality, and FLEMOps+ includes private precautionary measures and water contamination (Thieken et al. 2008). Elmer et al. (2010) have further developed these models to include recurrence intervals, FLEMOps+r. The functions used in FLEMOps-family are step-functions (Figure 3). Except from Yang et al. (2015) that could not find any clear advantage of using multifactorial RFDFs for Bangladesh, peer reviewed literature show that simultaneously accounting for several damage influencing variables improve the reliability of flood damage modeling (Elmer et al. 2010b, Gerl et al. 2014, Schroter et al. 2014, Thieken et al. 2008), the FLEMOps+r performs particularly well (Elmer et al. 2010b). The down-side of multifactorial models is that they are extremely data demanding (Gerl et al. 2014).

The large set of studies emphasizing the variety of circumstances that impact extent of flood damage together with the low predictability of the variable flood depth alone indicate that more research should focus on including more damage influencing variables into damage estimation.

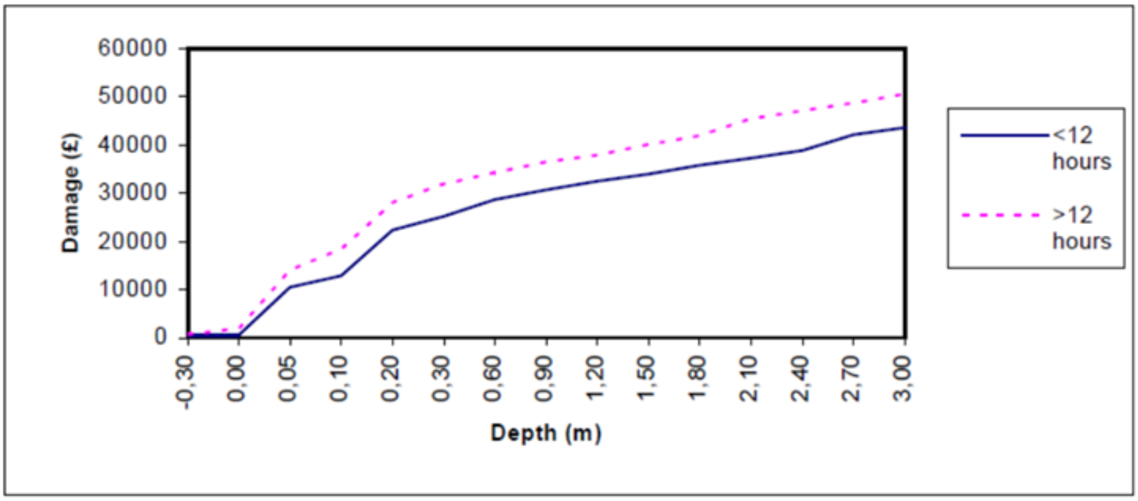

Figure 3: RFDF taking account for depth and duration. Source: Messner et al. (2007), Penning Rowsell (2003).

Validation

Scientists have repeatedly emphasized the importance of reliable RFDFs (Elmer et al. 2010, Yang et al. 2015). Validity and reliability are closely connected (Messner et al. 2007). A validation process assesses the correctness and completeness of tools, models or methods to accurately measure what it is intended to measure, often using statistical methods. Concerning RFDFs, validation is an assessment of the extent to which the RFDF in question is capable of accurately estimating damage to residential buildings when actually or potentially exposed to flooding. The importance of the RFDFs is rooted in the impact they can have on final outcome of quantitative flood risk assessments and the increasing importance such approaches have when deciding upon appropriate actions to reduce risk, in the short-term as well as in the long-term, and its role in guidance when deciding upon what areas are effective to protect. The higher reliability and accuracy, the lesser the burden of uncertainty upon the decision making process. Modeling uncertainties are typically neglected in flood loss assessments and researchers are only beginning to understand their effect on the robustness of flood loss estimates (Tate et al. 2014).

Despite the enormous amount of damage functions applied in practice, there are few regular functions that are commonly used in scientific peer reviewed literature. All functions included in the validation section of the review are listed in Table 3 with a description of the type of function, the influencing variables used, the functional form and the country where the function has been applied.

Table 3. Functions applied in "validation" studies.

Function	Type of function	Damage influencing varaible	Functional form	Country of origin	Applied by authors
Rhine Atlas	empirical, synthetic, realtive, depth-damage	dept	$Y= (2x^2 + 2x)/100$	The Rhine Catchment	Albano et al. (2015), Apel et al. (2009), Bubeck et al. (2011), Cammerer et al. (2013), de Moel & Aerts (2011), Jongman et al. (2012), Thieken et al. (2008), Wünsch et al. 2009)
MURL	relative, depth-damage	depth	Y=0.02x	Germany	Apel et al. (2009), Cammerer et al. (2013), Thieken et al. (2008), Wünsch et al. (2009)
Hydrotech	realitve, depth-damage	depth	Y=(27 sqrt(x))/100		Apel et al. (2009), Cammerer et al. (2013)Thieken et al. (2008), Wünsch et al. (2009)
Damage Scanner	synthetic, realtive, depth-damage	depth		Netherland	Albano et al. (2015), Bouwer et al. (2009), Bubeck et al. (2011), de Moel et al. (2012), Jingman et al. (2012)
The Multic-coloured manual	synthetic, absolut, depth-damage	depth		U.k	Albano et al. (2015), Jongman et al. (2012)
Geoscience Australia (GA)	synthetic relative depth-damage	depth		Australia	Hasanzadeh Nafari et al. (2016)
USACE/HAZUS	emprirical, syntehic, relative depth-damage	depth		USA	Albano et al. (2015), Hasanzadeh Nafari et al. (2016), Jongman et al. (2012), McGrath et al. (2015), Pistrika et al. (2014), Tate et al. (2015)
FLFArs	stage-damage	depth		Australia	Hasanzadeh Nafari et al. (2016)
FLEMOps	empirical, relative, multifactorial	considers depth, building type, building quality		Germany	Albano et al. (2015), Apel et al. (2009) Cammerer et al. (2013), Elmer et al. (2010), Jongman et al. (2012), Thieken et al. (2008), Wünsch et al. (2009)
FLEMOps+	empirical, relative, multifactorial	considers depth, building type, building quality, water contamination, precautinary measures		Germany	Albano et al. (2015), Apel et al. (2009), Cammerer et al. 2013), Elmer et al. (2010), Thieken et al. (2008)
Flemis model	synthetic, realtive, depth-damage	depth		Belgium	Albano et al. (2015), de Moel & Aerts (2001), Jongman et al. (2012)
JRC	empirical, synthetic relative depth-damage	depth		Europé	Albano et al. (2015), Jongman et al. (2012)
Standard method	syntehtic	depth, flow		Netherland	Albano et al. (2015)
Netherlands Later curves	relative, depth-damage	depth		Netherland	de Moel & Aerts (2011)
Moschato step function	empirical, relative, depth-function	depth		Greece	Pistrika et al. (2014)
Palermos	empirical, relative, depth-damage			Italy	Pistrika et al. (2014)

This study has identified only four peer reviewed studies that mainly focus on validation of RFDFs (Table 4). Hasanzadeh Nafari et al. (2016) derive a new flood loss function, FLFArs, for Australia and calibrate it against observed 2013 Australian flood data. The study further estimates flood damage using the newly derived function and compares its output to output estimates produced by an Australian GA-function and an US USACE- function, when applying the RFDFs to a flood event occurring in Australia in 2012. The comparison shows that the accuracy of estimated flood damages strongly depends on the choice of RFDF. The GA and the USACE functions do not lie within the 95% confidence interval set as criterion for acceptable deviance, and their performance is therefore rejected in the study area. Flood estimation without model calibration can lead to inaccurate prediction of losses leading to either over or under estimation of losses.

Bubeck et al. (2011) analyze the reliability of flood damage estimates for the Rhine River. The study applies the two models, Rhine Atlas developed for the Rhine catchment, and the Damage Scanner developed in the Netherlands. Both models use single-parametric stage-damage RFDFs to estimate flood damage. Both functions, overestimated considerably the rate of damage to residential buildings when applied to the case study area. By comparing the outcomes produced by the two functions, the study shows that differences rely largely on the functional forms of the damage curves, producing results that in absolute values diverges between 3.5 and 3.8 when applied to the case study area.

Thieken et al. (2008) present the development and validation of multifactorial flood damage estimation models, FLEMOps and FLEMOps+. Outcome of damage estimates using the "new" RFDF's were compared to outcomes produced by single factor stage-damage functions (Rhine Atlas, Hydrotec, MURL), before validating all of them against datasets of observed repair costs. Results show that the multifactorial models FLEMOPs and FLEMOps+ perform better than simple stage-damage functions. They are, however, also burdened with large uncertainties and fail to estimate building losses at very high water levels. Mean relative error of estimates for FLEMOps+ varies between 24 and 1000 percent. An interesting aspect of this study is that the FLEMOps and FLEMOps+ are validated against the flood event used to derive them. The authors justify this by the fact that the number of reported loss records per municipality exceeds the number of interviews at least ten times, which means that the data set can be considered independent.

Downton et al. (2005) present a reanalysis of the USA flood damage database concerning the accuracy of US flood damage data. The study evaluates the accuracy by comparing a set of damage estimates with actual expenditures using data from the 1998 El Nino flood event in California. The study shows that individual damage estimates for small events (damage less than $50 million) or for local jurisdictions tend to be extremely inaccurate. Large under and overestimation occurs with similar frequencies and magnitudes. Over half of the preliminary damage estimates were in error by more than a factor of 1.5, and over half of the initial damage estimates were off by more than a factor of 2 (with many by more than a factor of 4). Further, disasters causing moderate damage are greatly underestimated using US damage data set. What can be seen, however, is that estimates of damage aggregated over time or aggregated over larger areas are more reliable and robust than for example estimates for single buildings or small residential areas.

Table 4. List of peer reviewed studies with main focus on validation.

Author	Publication	Objective	Approach	Results
Hasanzadeh Nafari et al. (2016)	Calibartion and validation of FLFArs- a new flood loss function for Australian residential structures	Derive a new flood loss function for Australia, calibrate it against empirical data and compare it to the ouput from two other models	The model is calibarted using empirical data, it is validated against observed losses in Australia flood 2013 and compared with the outcome of two other models, one Australian (GA) and one American (USACE) for estimating losses from a flood event in Australia in 2012	Estimated precision is strongly dependent upon choice of DF. Flood estimation without model calibartion can lead to inaccurate prediction of losses (over- or under estimation of losses). The GA and the USACE functions do not lie within the 95 % CI and their performance is therefore rejected in the study area
Bubeck et al. (2011)	How reliable are projections of future flood damage?	To evaluate the reliability of relative estimates of flood damage developments for the River Rhine with regard to different flood damage modelling appraoches	The study applies two damage functions to a case study area and compares the results	The results show that differences in estimates rely more on the functional forms of the damage curves (factor of difference: 3.5-3.8) than the differences in maximum damage that can be reached with the two different functions (factor of difference: 1.4). Proportional changes more robust than total estimates. The models overestimted by far the rate of damage to residental building and severely underestimted the rate of damage to infrastructure.
Thieken et al. (2008)	Development and evaluation of FLEMOps- a new Flood Loss Estimation Model for the private sector	To present a new model for the estimation of losses in the residential sector and its validation	Simple stage damage functions, FLEMOps and FLEMOps+ were validated against different datasets of observed repair cost for single buildings	Results show that FLEMOps+ outperformes the simple stage-damage functions. The model, however, fails to estimate the building loss at very high water levels.Overall, mean realtive error of estimates for FLEMOps+ varies between 24 and 1000 percent
Downton et al. (2005)	How accurate are disaster loss data? The case of U.S flood damage	The study present a reanalysis of the USA flood damage database.	Compares a set of loss estimates with actual expenditures using data from the 1998 El Nino flood disaster in California	Individual damage estimates for small events (damage less than $50 million) or for local jurisdictions tend to be extremely inaccurate.Large under- and overestimation occur with similar grequency and mangitudes. Over half of the preliminary damage estimates were in error by more than a factor 1.5, and over half of the initial damage estimates were off by more than a factor 2 (with many by more than a factor 4). Disaster causing moderate damage are greatly underestimated. Damage aggreagated of time or over larger areas are reasonably reliable.

Despite the scarcity of validation studies focusing directly on RFDFs, there are peer reviewed studies in the literature that have analyzed function uncertainty as a part of a larger objective of validating or comparing more comprehensive hazard models with the purpose of analyzing the share of uncertainty contributed by two or more of the model components; hazard, exposure and vulnerability, to the final risk estimation outcome (Apel et al. 2008, deMoel and Aerts 2011, Jongman et al. 2012, Tate et al. 2015), or developing models (Pistrika et al. 2014), transferability of functions (Cammerer et al. 2013) or the effect of flood frequency (Elmer et al. 2010b). Sixteen studies where vulnerability is completely or partly represented by RFDFs have been identified and listed in the appendix of this review (see Table A1 in the appendix).

Most of the studies are not directly comparable at a detailed level since their approaches differ in terms of statistical methods, the included RFDFs, the applied data set, and/or whether damage estimation results have been validated against actual observed damages (costs or ratios). Studies that do validate or compare their estimates against observed damages are McGrath et al. (2015), Gerl et al. (2014), Cammerer et al. (2013), Jongman et al. (2012), Elmer et al. (2010b), Apel et al. (2009), Wünsch et al. (2009), Merz et al. (2004). Despite the above mentioned differences, most studies indicate that the choice of RFDF significantly affects the final risk outcome (Albano et al. 2015; McGrath et al. 2015; Pistrika et al. 2014; Jongman et al. 2012; Boettle et al. 2011; de Moel and Aerts 2011, Elmer et al. 2010, Apel et al. 2009; Wünsch et al. 2009; Apel et al. 2008).

Despite their important role in flood risk assessment, the uncertainties of estimations are large when using RFDF for flood risk assessment. Albano et al. (2015) find that, depending upon choice of RFDF, the damage rate varies between 25% and 70% of total exposed asset value. Pistrika et al. (2014) finds that at 0.5 m water depth the damage ratio varies between approximately 4% and 23%. This is not directly comparable with deMoel and Aerts (2011) finding that at a water depth of 0.5 m their damage estimates varied between €1.26 billion and €6.86 billion depending upon choice of RFDF applied in the south of the Netherlands. In Albano et al. (2015), the most spatially compatible RFDF (the Palermo function) gives acceptable estimation of flood damage in the case study area, underestimating losses by only 10 percent. Tate et al. (2014) perform an internal model validation using global sensitivity analysis. This means that results are not validated against observed actual damage data, instead Monte Carlo simulations are used to generate loss distributions for studying the reliability of the estimates. Three different sets of RFDFs represent the uncertainty that damage functions contribute with to the overall model uncertainty (all three which are imbedded in the Hazus modeling tool). The upper bound loss distributions were found to be three times higher than the lower bound distribution. Choice of digital elevation data were found to be the most influential contributor to uncertainty in the final risk estimation outcome, however, choice of RFDF function was close behind.

Cammerer et al. (2013) analyze Austrian flood damages and find that in the case of more extreme events, estimated flood losses to residential buildings range with a factor 18 between the highest and the lowest estimates, depending upon which RFDF was used for the estimation. Jongman et al. (2012) present a qualitative and quantitative assessment of eight flood damage models that might be the most comprehensive and conceivable evaluation of RFDF. The study accounts for uncertainties in hazard, exposure, and vulnerability stages of flood damage modeling using two case studies of past floods in Germany and in the U.K. Both function uncertainty and value uncertainty are discussed. The study finds that methods for deriving loss models vary strongly. Further, estimation results are very sensitive to uncertainty in vulnerability, due to the functional form of the depth-damage functions, and to exposure, which in the study is represented by asset values. Vulnerability uncertainties, however, have larger effect than exposure uncertainties on the final risk outcome. The choice of RFDFs gives relative difference in damage estimation with factors of 4-11. This can be compared with De Moel et al. (2012) which got factors between 4 and 8, and Bubeck et al. (2011) which got factors in the size of 3.5-3.8. The relative differences in estimates are largest with low inundation depths, 0-1 m (Jongman et al. 2012).

Jongman et al. (2012) further compared observed losses with estimated losses and found that applied functions both underestimate and overestimate losses. For the municipality of Eilenburgh (Germany) only one function is capable of satisfyingly estimating observed losses (± 10 percent). For Carlisle (UK) no function was close to estimating actual losses, in fact, they all heavily underestimated observed losses. DeMoel and Aerts (2011) also analyze the relationship between hazard, exposure, and vulnerability and their effect on the final risk outcome. They found that asset values and choice of RFDF can cause uncertainty of a factor of 2 in the final risk estimates.

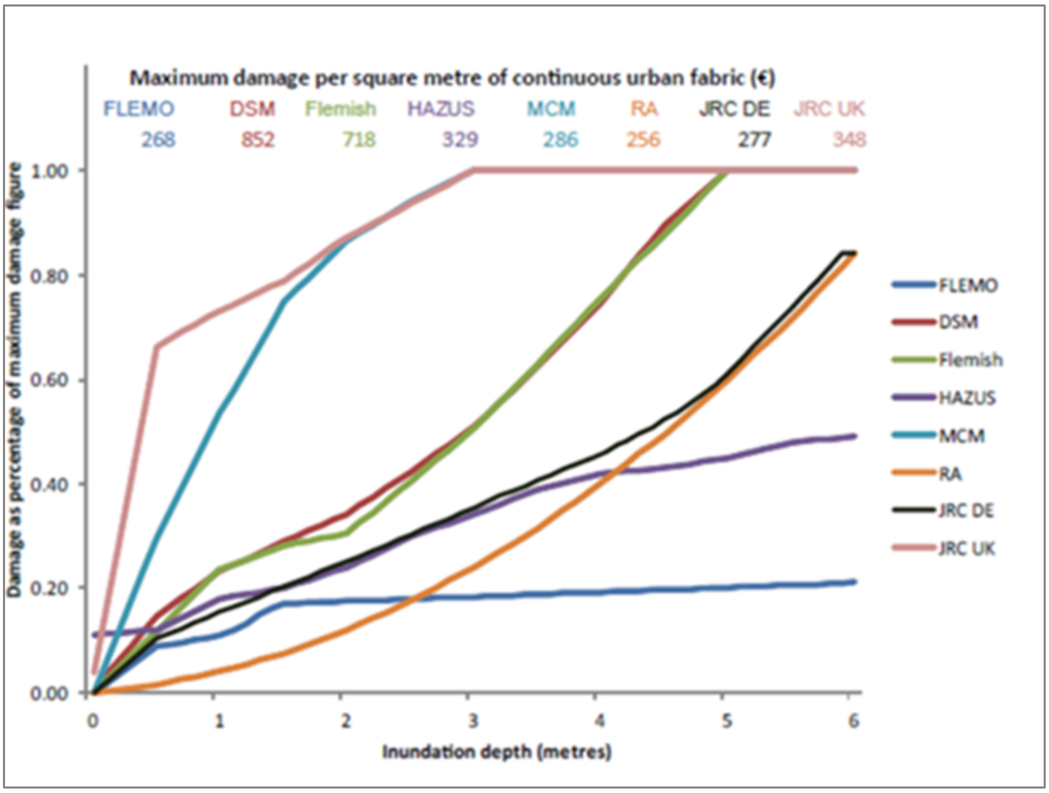

Figure 4: Examples of RFDF. The figure reflects the large variability in functional form of DF's. Source: Jongman et al. (2012).

Accounting for flood frequency when deriving or adapting RFDFs is highly important for the reliability of flood damage estimates. Merz and Thieken (2009) analyzed uncertainty bounds related to flood risk functions, letting 6 different RFDFs represent uncertainty in damage ratios. Their analysis imply that for return periods below 80 years the largest driver of total uncertainty in flood risk modeling is flood frequency, while uncertainty in damage estimates contribute with a smaller part. Elmer et al. (2010) modified five different functions (MURL, IKSR, HYDROTEC, FLEMOps, FLEMOps+) to include recurrence intervals, and then compared them to their unmodified counterparts. Performance was validated using Leave-one-out cross-validation method. The results show that unmodified models underestimate relative losses for events with long recurrence intervals and overestimate losses for more probable events with exception for FLEMOps+ which overestimate all events. A highly significant correlation was found between recurrence interval and loss extent. Elmer et al. (2010b) further emphasize that loss estimation should not apply the same function to low and high probability events.

Merz et al. (2004) quantify uncertainty associated with flood damage estimates of direct monetary flood damage to buildings. To test the usefulness of depth-damage functions, a non-parametric regression function between total damage and water depth was performed using observed damage data from floods in Germany between 1978 and 1994. The analysis reflects an enormous variation in damage estimates. For example at water depth of 1 m, damage to private housing varies from 375 Deutsche Mark, DM,to 63 527 DM. Merz et al (2004) conclude that absolute depth-damage function are not very useful for explaining variability in observed damage data. Given the enormous uncertainty of flood damage estimates, cost-benefit analysis of flood defense schemes will be highly uncertain.

The overall conclusion that can be drawn from the above studies is that risk estimations are more sensitive to uncertainties in damage vulnerability (V), due to functional form of the RFDFs, than to uncertainties in Hazard (P) or exposure estimation (E). Figure 4 reflect the large variety of functional forms of RFDFs. A few studies, however, divert from this conclusion. Merz and Thieken (2009) found that the RFDFs only contribute with a small share of the total risk estimation uncertainty. Tate et al. (2015) found that the Digital Elevation Model (DEM) was the most influential contributor to uncertainty of the final risk estimation (with RFDFs close behind) and Bottle et al. (2011) found that for small events, uncertainties related to the DEM affected the outcome more than the properties of the RFDF. Additionally, the reliability of flood damage estimation can be said to be fairly unknown. There is a large degree of uncertainty in the construction of RFDFs, the asset values connected to the functions and the larger methodological issues such as the spatial scale (object versus area-based) and damage function type (absolute versus relative) (Jongman et al. 2012). External validation of flood loss estimation models is a persistent shortcoming due to limited or non-existent post-disaster building damage information and uncertainty in loss estimates can be heavily influenced by the data and methods used in the modeling process (Tate et al. 2015).

From reviewing the different uncertainty, sensitivity and validation studies, results highlight the existence of large uncertainties concerning a number of components in flood risk estimation, leaving huge responsibilities upon the individual analyst to perform flood assessments. Applying RFDF to policy appraisal may serve as guidance for choosing efficient strategies, but with the risk that RFDF could over or under estimate future potential flood damages. More effort should be put into validation of RFDFs to decrease uncertainty in decision making. The main hurdles to performing comparable validation studies is availability of damage data, homogeneity of available damage data, and the lack of spatially and timely overlapping damage data sets and research should focus on how to overcome these hurdles.

Based on the above studies, there are four main elements concerning vulnerability and exposure to flooding that contribute to uncertainty in risk estimations. The first and second elements are directly related to RFDFs, and need to be assessed in a flood risk assessments. The third and fourth elements contribute with estimation uncertainty feeding into the overall uncertainty of the risk assessment:

1. Uncertainty related to the elevation model. Quality and resolution of elevation models affect assumption related to inundated areas (exposure).
2. Uncertainty related to hydraulic modeling. Assumption and estimation of discharge volumes and velocities affect assumptions related to inundated areas and vulnerability of objects at risk (exposure, vulnerability).
3. Uncertainty related to the building inventory. Uncertainty related to key building attributes: location, first-floor elevation, building type, and content of buildings.
4. Uncertainty related to damage estimates (vulnerability of objects at risk) and the asset values applied in derivation of relationships or combined with the estimated vulnerability index.

Transferability

The validity of functions and transferability of RFDFs are to some extent related issues. Flood models and damage functions often rely on a significant amount of input data. Risk and emergency managers in many countries lack the necessary standardized tools to adequately perform reliable risk assessments (Nastev and Todorov 2013). The increased focus on economic efficiency of flood alleviation has made attractive to adapt or directly apply RFDFs derived elsewhere. Imported RFDFs have been seen as an easy solution to countries and regions with limited data availability, experience, and other resources, since it has been seen as the least data demanding, least expensive and least time consuming option to perform quantitative damage analysis to residential areas. Transferability of models to other geographical regions is, however, still a major gap in flood damage modeling (Albano et al. 2015).

Meyer et al. (2013) question to the extent to which transferring damage functions is at all possible. This is supported by Thieken et al. (2008) that consider the transferability of damage models to regions other than those for which they were derived to be very limited, and by Hasandzadeh Nafari et al. (2016) emphasizing that Australian RFDFs are not flexible for transferring in spatial scale or in time. Cammerer et al. (2013), however, found, when evaluating the transferability of nineteen RFDFs to an Austrian region by comparing them to official 2005 losses, that functions adapted from homogenous regions and floods, estimated observed damage well. Cammerer et al. (2013) found that RFDFs derived from more heterogeneous datasets clearly overestimated flood damages in the case study area. Pistrika et al. (2014) applied data that was deemed highly compatible both spatially and damage wise. With high compatibility of input data and RFDFs the damage estimates differed by 10 percent, making the authors conclude that with lower compatibility, there will be large difficulties in obtaining acceptable functions.

Jongman et al. (2012) compared eight different models using region or country- specific information estimating flood damage at individual or regional scale, applied to one municipality in both the UK and Germany. They found that the spatial heterogeneity of exposure values and RFDFs strongly affect uncertainties in estimations when transferring the models to other areas. Green et al. (2011) indicate that asset values (and their role in estimation uncertainty) are directly related to GDP per capita. Jongman et al. (2012), however, account for this by testing the JRC-model, which corrects for differences in GDP, and finds that correcting only for GDP does not satisfactorily increase the capacity of the model. Furthermore, Jongman et al. (2012) underline that differences in predominant building style, household income, regulations, and flood insurance practices are factors that also must be adjusted for. Transferred functions to new geographical conditions do not establish appropriate relationships between the magnitude of the flood and the value of exposed assets unless they have been adjusted to local conditions (Hasanzadeh Nafari et al. 2016).

Despite the knowledge gaps related to the transferability of RFDFs, many damage models are transferred in space and time without further validation (Cammerer et al. 2013, Merz et al. 2010). Adapting flood risk assessment models and RFDFs is often presented as an "easy" solution, being less expensive and less data and time- demanding, but the adjustments are complicated. They require that the analyst is well aware of the pitfalls of transferring functions. Adjustments demand knowledge of the assumptions and development of damage functions, good familiarity with the function that might be suitable to transfer, and knowledge of the local conditions to which it is to be applied.

When transferring damage functions there is a new dimension of uncertainty added to the risk assessment due to changed local conditions. A theory of the relationship between damage inducing factors and the extent of damage should form the foundation for the choice of the function. It is essential to adjust asset values to the regional economic situation and property characteristics. Flood damage estimation without adapting to local conditions and without validation can result in inaccurate prediction of losses and thereby raise the uncertainty in flood damage assessments. Unsuccessful adaptation of RFDF can lead to biased estimations and production of misleading risk management guidance.

Since research on transferability of damage functions is scarce, there are no standard procedures. Based on the reviewed literature and identified knowledge gaps, the adjustment procedure should include evaluating and adjusting for the following aspects:

- Type of flooding: warning time, velocity, duration, contamination, and time of year.
- Type of buildings and density of built up areas: structures and building material.
- Economic factors: GDP and household income.
- National/regional/local regulations.
- Flood insurance practice.
- Historical actual flood damage, if possible.

Transferability of method and functions to developing countries

Residential flood damage functions have mostly been developed in and for developed countries to reflect economic efficiency of flood alleviation. Developing countries are starting to adopt this approach to flood risk assessment. In a study by Hochrainer-Stiegler et al. (2010), the cost estimation for floods in Jakarta is based on FEMA methodology. Transferability of functions is low even between and within countries of similar structures, which raises the question of whether these functions can be transferred to developing countries. There are also examples of developing countries, such as Argentina, adapting the method to construct country specific functions based on their own country specific data (World Bank 1996). Here, the functions reflect the country specific vulnerabilities but still face the same challenges of vulnerability and reliability as the one used in developed countries.

Equity and fairness in flood damage assessment

Flood damage functions only estimate the asset values at risk of flooding. Most commonly market values, construction costs, or restoration costs are used as the basis for estimation of direct monetary losses (potential benefits of mitigation measures). Lower quality buildings and areas mostly occupied by lower social classes are valued less than higher social classes (FEMA 2014, Penning-Rowsell and Chatterton 1977, Penning-Rowsell et al. 2013). This is also the case when estimating the value of contents. Lower social classes are assumed to possess content of lower value. Flood damage assessments often focus on private housing (Meyer et al. 2013), so therefore when damage functions are used as input to a cost-benefits analysis, residential areas and damage to buildings become very influential on the outcome of the analysis. In practice, the socio-economic status of occupants are used when assigning potential damage values, such as in the US Hazus-model, census data is used to classify occupants into economy, average, custom or luxury-classes (Tate et al. 2015). In the UK, RFDFs are divided into four social classes where the property of unskilled manual workers and state pensioners are assigned the lowest values, and higher managerial, administrative or professionals the highest (Penning-Rowsell and Chatterton 1977). Also, in the UK, if deemed to be necessary and practical, weighted factors can be used to account for distributional analysis that takes into account the socio-economic differences (Penning-Rowsell et al 2013). These weighting factors are not to be applied to average values since average values are perceived to be weighted (Penning-Rowsell et al. 2013). Using average asset values or average damage values is seen as one simple way of assigning values to RFDFs. The approach distributes the same value to all properties independent of their actual value or the social class of the occupants. Such a lower level detailed damage function might be perceived as fair but is still problematic due to the declining marginal value of income. An impact estimated at €1000 damage might be of less concern to a wealthy property owner than to a low income person. Occupants belonging to higher social classes are believed to be better equipped to handle the shock a flood event imposes on the private economy and to have shorter recovery time (Penning-Rowsell and Pardoe 2012). Indirect effects to impacted lower social classes have been known to adversely affect the poor more than the rich (Penning-Rowsell and Pardoe 2012). It is essential to consider which areas benefit most from a measure and which areas do not (Albano et al. 2015).

If a decision is driven by economic analysis (for example, a cost-benefit analysis), which takes overall economic efficiency to society into account, this will leave the distributional aspects to the decision maker. Distributional effects of flood risk reduction are, however, rarely considered (Penning-Rowsell and Pardoe 2012). In the reviewed literature, equity, fairness and distributional issues are not at all addressed or only briefly touched upon (in for example Brouwer and van Ek 2004 and Davis 2016). For policy purposes, however, it is important to know who suffers the most in the aftermath of a hazard (Meyer et al. 2013). Flood impacts are not distributed equally throughout society. It is important to be aware that estimating damage impacts using damage functions do not explicitly consider distributional effects. It is supposed to objectively account for actual asset values within areas at risk of flooding. "Rich areas" are assigned higher values, if not corrected using weighing factors (see Table 5 for an example of weighting factors). Using RFDF to evaluate different flood alleviation projects within the same area will not raise any equity concerns but using the same RFDF to estimate efficiency of flood protection in two separate areas of different social class will raise issues of fairness since the property of the affluent residents will be valued higher and, therefore, have higher impact in a cost-benefit analysis, leading to low income areas being worse off in an economic analysis. These aspects are also applicable to the relationship between rural areas and urban areas. Urban areas with higher property density will be more efficient to protect. Currently, however, distributional aspects commonly lie in the hands of the policymaker.

Table 5. Example of weighing factors used to adjust for distributional differences in the UK. AB, C1, C2, and DE represent social classes

AB	C1	C2	DE
0.74	1.12	1.22	1.64

Source: Penning-Rowsell et al. 2013.

Transparency

A presumption, and key issue, for good guidance on policy formulations is transparency in assessments. Awareness of basic underlying assumptions, uncertainties, limitations of model approaches and distributional issues are of most importance. Unfortunately, the transparency of flood risk assessments is generally poor. For example, Brouwer and Van Ek (2004) performed a comparison between cost-benefit analysis and multi-criteria analysis methods, focusing on their capacity to integrate environmental, ecological, social, and economic aspects of flood risk mitigation. They perform this comparison with the key omission of interrogating the benefit estimation. In relation to benefit estimation the authors simply state that they have applied the "DWW- approach", referring to a Dutch publication (DWW 2000), which estimates the benefits of material damage avoided to be in the order of 300 billion Euro. The validity or reliability of applied damage function is not mentioned and reflection on how the function uncertainties or the uncertainty in the applied assets might affect the 300 billion Euro outcome is non-existent in the study. A similar example is a study by Jonkman et al. (2004) that uses a cost-benefit analysis as an approach to flood damage mitigation in the Netherlands. RFDFs are mentioned in the theoretical framework, but when the benefit estimation is described in two practical settings, there is no mention on how the benefits have actually been estimated, let alone an appraisal. Opinion is, however, expressed by the authors that the estimated damage that potentially could be avoided by the mitigation project under evaluation was "too high" due to unrealistic assumptions of asset vulnerability (estimated using RFDFs). While lower numbers on avoided damages were suggested as more reasonable, no explanation was offered on how these estimates were derived.

Another reason for limited transparency is the technical development, the practice of embedding damage functions into software programs. Numerous software tools are available to perform loss estimation for riverine flooding (Jongman et al. 2012, Merz et al. 2010, Tate et al. 2015), such as HIS-SSM in the Netherlands and Multi-coloured manual in the U.K (Bubeck et al. 2011, Penning-Rowsell et al. 2013). One example is the GIS-based software developed by FEMA, HAZUS-MH, which is the leading model for community and regional-scale estimates in the United States (Banks et al. 2014, Tate et al. 2015). The tool links probabilistic and deterministic models (elevation model, hydraulic model, elements at risk of flooding, and building damage models) for estimation of physical damage and economic loss caused by earthquake, river and coastal floods, and hurricanes (Tate et al. 2015). It includes baseline (default) information on flood scenarios, buildings characteristics and damage, and contains a portfolio of more than 900 RFDFs that the analyst can choose from (Scawthorn et al. 2006). Users can also replace the baseline data with their own area specific data. In addition to residential areas, the HAZUS software also has the potential to estimate damage to businesses, industry, and transportation infrastructure, although residential buildings are the most frequently modeled element (Tate et al. 2015). For more information on the HAZUS software tool and its application and uncertainties see Tate et al. 2015, Scawtorn et al. 2006, and FEMA 2014 and 2016.

Technical progress has, however, made it possible to handle different scenarios and an enormous amount of input data within one model and also lowered the level of expertise needed to perform this type of flood risk assessments. It has made it more assessable and applicable, but also made it possible for analysts to be unaware of the functional forms of the underlying RFDFs, their basic assumptions, and the implications of their choice on the outcome of the flood risk estimations. The damage functions are buried within databases or only documented and described in various technical, user manuals, and reports, and therefore not available for direct evaluation.

For even the most diligent policy maker, it can be extremely challenging, or even impossible to untangle the assumptions and the completeness of a risk estimate. RFDFs have mostly been developed by engineers for engineers (Grigg and Helweg 1975). Uncertainties related to damage functions are well known by the model developers but rarely transparently communicated to policy makers; a situation which has been magnified as models have become more detailed and complex.

Conclusions

RFDFs have long been accepted as a standard approach in practical settings but they are not scientifically motivated and surprisingly underrepresented in peer-reviewed literature in comparison with hazard and exposure analysis. Despite their importance in policy making, the development of flood damage functions, their basic assumptions, their ability to represent actual flood damage, and their validity have been poorly represented in scientific literature. An understanding of the role damage functions have in deriving efficiency measures for project appraisal is crucial for policy formulation. A large variety of single-parameter RFDFs exist and the responsibility of implementing a function suitable for the area to be analyzed lies upon the user (risk analysist, risk manager). Despite the existence of better performing multi-factorial models, the questionable single factor depth-damage function is still the most commonly applied function, in practical application and in research. Damage estimates derived using RFDFs are burdened with high uncertainty and risk assessment models incorporating RFDFs are rarely validated.

This review has found the transferability of RFDFs is low. Functions are highly temporally and spatially context-specific, and transferability of RFDFs beyond this context is questionable. When transferred functions are used in risk assessments this should be clearly stated along with the appropriate adjustments undertaken. Due to the increased uncertainty related to the issue of transferability, policy makers should pay special attention to assessments where transferred functions have been applied. Furthermore, transferability of functions derived in developed countries for use in developing countries is highly questionable. Adaptability of methods and transferability of damage functions between developed and developing countries have not been investigated rigorously, indicating a key area of future study.

The way RFDFs are developed and incorporated into risk assessments does not consider the distributional consequences. Distributional issues can be corrected for within RFDF estimation but is rarely done. Addressing distributional issues in relation to quantitative risk assessments is still very much the responsibility of policymakers, a task which is further complicated by the lack of transparency. Transparency of RFDFs and their role in quantitative risk assessment is low. This is a barrier to approach the above mentioned challenges and also makes the risk assessment more uncertain and less reliable.

The residential flood damage function is, and will continue to be, an important part of the risk equation (R =P x E x V), as an efficiency measure, but also as a way of comprehensively communicating vulnerability. The large uncertainties in the estimates are, however, very troubling and more research effort must be put into validation of the functions, estimating their uncertainty and increasing their reliability. Extra effort should be focused on transferability of functions, especially between developed and developing countries. Policymakers must be made aware of the large uncertainties and the implications this has for transferability of functions and equity issues when applying damage functions for policy guidance.

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Appendix

Table A1. List of studies that address RFDF uncertainty or validity.

Author	Publication	Main objective of study	Approach to DF analysis	Results
Albano et al. (2015)	Collaborative strategies for sustainable EU flood risk management: FOSS and geospatial tools- Challenges and opportunities for operative risk analysis	Organize available knowledge and characteristics of methods and principles into operational recommendations	Compare 8 DF's with input from one data set provided for a workshop on the benchmarking of risk analysis for dam breaks. Results are not validated against empirical flood losses.	Choice of function sign. affect the final result despite using identical hazard- and land use data and depending upon choice the damage rate varies between 25% and 70% of total value
McGrath et al. (2015)	Sensitivity analysis of flood damage estimates: A case study in Fredricton, New Brunswick	Analyses epistemic uncertainty related to adapting US Hazus model to Canadian condition by reviewing and varying DF's, flood depth (hazard) and restoration duration. Sensitivity analysis is performed for every part of the model to determine how the different parts influences the final results	Comparative analysis. 85 DF's were applied to a case study area to analyze the variability in damage estimates related to choice of DF. The results where compared to estimation results by default functions and to actual flood losses in the city of Fredricton in 2008.	Loss estimates indicate that choice of DF have significant impact on final results.

Tate et al. (2015)	Uncertainty and sensitivity of the Hazus- MH flood model	Estimate the uncertainty of flood loss estimation and the relative contribution of each model component to the overall uncertainty	Internal model validation using Global sensitivity analysis. Monte Carlo simulations are used to generate loss distributions. Results are not validated against actual observed flood losses. Three different sets of DF's represent the uncertainty that DF's contribute with to the overall model uncertainty (all three are imbedded in the Hazus modeling tool)	The upper bound loss distributions were found to be a factor 3 higher than the lower bound distribution. Choice of digital elevation data were found to be the most influential contributor to uncertainty of the final outcome, but the depth-damage functions was close behind in importance
Gerl et al. (2014)	Flood damage modeling on the basis of urban structure mapping using high-resolution remote sensing data	Examines how valuable information about the spatial distribution of residential buildings types and characteristics derived from remote sensing can be utilized to improve multi-parameter flood damage models	The DF FLEMOps and regression-tree models are adapted to the building stock information derived from remote sensing data and calculated based on residential buildings types from the urban structure map. Estimated losses are compared to official losses caused by the Elbe flood in 2002	The estimated losses caused by the Elbe flood in 2002 are in same order of magnitude as the official damage data

Pistrika et al. (2014)	Flood depth-damage functions for built environment	Derive local DF's and describe step-by-step development of empirical relative depth-DF using data from a flood event in Athens, Greece in 2002, and compare them with functions derived elsewhere	The newly derived local DF is compared to 5 other functions derived for other geographical areas. Then the newly derived function and the spatially most similar other function (Palermo) are both applied to a third area in Greece. Results are not validated against empirical flood data except for the Palermo function that is applied to the Athens 2002 data.	The estimates vary considerably depending upon choice of DF. At 0.5 m the damage ratio varies between app. 4% and 23%. The most spatially compatible DF (Palermo function) gives acceptable estimation of the 2002 Athens flood data, but underestimating losses by 10%. The two DF's are deemed to give acceptable results when applied to a third area to estimate annual damage. The estimated annual damage to however differ by 9.2% (this time the Palermo function gives the highest estimate)
Cammerer et al. (2013)	Adaptability and transferability of flood loss functions in residential areas	Evaluate transferability of various flood damage models to an Austrian region	19 DF's have been adapted to the Austrian region and compared to official flood losses of 2005	In the case of extreme events, estimated flood losses to residential buildings ranges, between the highest and the lowest estimates, to a factor 18, depending upon choice of DF

de Moel et al. (2012)	Uncertainty and sensitivity analysis of coastal flood damage estimates in the west of the Netherlands	To perform uncertainty and sensitivity analysis of flood damage estimates, including uncertainty in hazard input parameters and damage calculations, using the model; Damage Scanner	Monte Carlo simulations are used to test the impact of different input parameters. Concerning the damage function, uncertainty bands were designed for two parameters; Max. asset values at risk and the shape of the curves. The analysis compares the variation of input values to the model default parameter values. Results are not validated against empirical flood damages.	The most influential parameter in flood damage modeling is uncertainty in depth-damage functions

Jongman et al. (2012)	Comparative flood damage models assessment: towards a European approach	To present a qualitative and quantitative assessment of 8 flood damage models. Taking account for uncertainties in hazard-, exposure-, and vulnerability stages of flood damage modeling	Compares 8 flood damage functions using two case studies of past floods in Germany and the U.K. The models are compared qualitatively and quantitatively. Both functions uncertainty and value uncertainty are discussed.	Modeling approaches varies strongly. Estimation results are very sensitive to uncertainty in vulnerability (due to the functional form of the depth-damage functions) and exposure (asset values). Vulnerability uncertainties, however, have larger effect on the outcome than the exposure uncertainties. The relative differences in estimates are largest with low inundation depths (0-1 m). Estimation of function uncertainty (vulnerability) gives relative difference factors of 4-11. When comparing observed losses with estimated losses the applied functions both underestimate and overestimate losses.
Boettle et al. (2011)	About the influence of elevation model quality and small-scale damage functions on flood damage estimation	Estimate the direct monetary damage to buildings and study the influence different modes (inundation, elevation, coarse-graining, and damage function) of this appraoch on the macroscopic damage function	3 DF's (linear, square root and quadratic) are applied to a case study area in Denmark. Results are not validated against observed losses	For small events, the macroscopic damage function mostly depends upon on the properties of the digital elevation model (DEM). For large events the macroscopic function strongly depends on the assumed building damage function

de Moel and Aerts (2011)	Effect of uncertainty in lands use, damage models and inundation depth on flood damage estimates	Assess the influence of uncertainty in the four components of a flood risk model (hazard, exposure, asset values, susceptibility of assets)	3 DF's are combined with hazard and exposure models and compared by manually varying the components in a "one factor at a time" approach. Results are not validated against empirical data	Value of assets at risk and choice of DF's are the most important source of uncertainty in final risk estimates. For example, at 0.5 m damages varies between 1.26 billion and 6.86 billion depending upon choice of DF. Both asset values and choice of DF can cause uncertainty of a factor 2 in the final risk estimates
Elmer et al. (2010)	Influence of frequency on residential building losses	To analyze the relation between flood damage and recurrence interval and to propose a method for considering recurrence interval in flood loss modeling, based on loss data from 2002, 2005, and 206 in Germany	5 functions (MURL, IKSR, HYDROTEC, FLEMOps, FLEMOps+) were modified to include recurrence intervals, then compared to their unmodified function. Performance were validated using Leave-one-out cross-validation method	The models that don't account for recurrence intervals all underestimate relative losses for events with long recurrence intervals and overestimate losses for more probable events with exception for FLEMOps+ which overestimate all events. Loss estimation should not apply a uniform function to low and high probability events
Merz and Thieken (2009)	Flood risk curves and uncertainty bounds	Flood frequency analysis, inundation estimation, damage estimation and quantification of total uncertainty	6 different DF's represents uncertainty in damage ratios. Uncertainty in asset estimation is not accounted for	Damage estimates contribute with a small share of the total uncertainty. For return periods below 80 years the largest contributor is flood frequency, for return periods of more than 82 years the inundation estimation is the largest contributor

Apel et al. (2009)	Flood risk analyses- how detailed do we need to be	To perform a comparative risk analysis study (hazard analysis and vulnerability analysis)	5 different flood DF's (together with 3 hazard models) are applied to the municipality of Eilenburg at the river Mulde and compared to actual flood damage occurring in 2002	Selection of flood loss models have larger effect on the final risk outcome than the selection of hazard models
Wünsch et al. (2009)	The role of disaggregation of asset values in flood loss estimation: A comparison of different modeling approaches at the Mulde River, Germany	Application and evaluation of several common disaggregation methods in the framework of flood loss estimation	4 different DF's were used to estimate and compare final outcome and the impact disaggregated hazard and exposure data has on flood loss estimation. Final outcome was also compared to official repair cost in 19 communities after the 2002 floods in Germany	The 4 different DF's give very different results independent of disaggregation methods, indicating how influential choice of DF is. The MURL function (derived for the River Rhine) constantly underestimate the flood losses by 50% or more in all communities. The MURL function is not applicable to the Elbe catchment. ICPR and FLEMOps functions produce the most similar estimates, however, they both have a tendency of underestimation. The HYDROTECH function overestimates building losses with a 100 percent or more. The specific characteristics of DF's are apparent.

Apel et al. (2008)	Quantification of uncertainties in flood risk assessments	Develop method for assessing flood risk along river reaches. Quantify the different sources of uncertainty. Compare uncertainty reducing effect of additional information	The study uses Monte Carlo simulation to estimate the relative influence of uncertainty in different modeling stages (hazard, vulnerability). 3 different DF are used in the simulation to represent damage estimation uncertainty (ICPR, MURL and HYDROTEC)	Extrapolation of data far beyond the length of the dataset generates highly uncertain estimates. Uncertainty in both hazard- and damage modeling have large influence on simulated risk. The 3 DF's produce very different damage estimates
Merz et al. (2004)	Estimation uncertainty of direct monetary flood damage to buildings	Quantify uncertainty associated with flood damage estimates	To test the usefulness of depth-damage functions a non-parametric regression function between total damage and water depth was performed using observed damage data from flood in Germany between 1978-1994.	The analysis reflects an enormous variation in damage estimates. For example, at water depth of 1 m, damage to private housing varies from 375 DM to 63 527 DM. Absolute depth-damage function are not very useful for explaining variability in observed damage data. Given the enormous uncertainty of flood damage estimates, cost-benefit analysis for flood defense schemes may be highly uncertain

”Despite the existence of better performing multi-factorial models, the questionable single factor depth-damage function is still the most commonly applied function, in practical application and in research.”

This study assesses the development and use of flood damage functions and goes on to identifiy key issues to improve their use in policy decision making. The results of this study indicate that the extent of asset damage due to flood depends on several factors such as water depth, flow velocity, duration, pollution level, building features, time of occurrence, warning, previous experience, and private precautions, among many others. Multi-factorial models perform much better than single factor models in predicting damages, but they are rarely used.

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