



Flood loss estimation using 3D city models and remote sensing data

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ABSTRACT

Flood loss modeling provides the basis to optimize investments for flood risk management. However, detailed object-related data are not readily available to generate spatially explicit risk information. Virtual 3D city models and numerical spatial measures derived from remote sensing data provide standardized data and hold promise to fill this gap. The suitability of these data sources to characterize the vulnerability of residential buildings to flooding is investigated using the city of Dresden as a case study, where also empirical data on relative flood loss and inundation depths are available. Random forests are used for predictive analysis of these heterogeneous data sets. Results show that variables depicting building geometric properties are suitable to explain flood vulnerability. Model validation confirms that predictive accuracy and reliability are comparable to alternative models based on detailed empirical data. Furthermore, virtual 3D city models allow embedding vulnerability information into flood risk sensitive urban planning.

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1. Introduction

With the transition to flood risk management, for which flood risk analyses are an essential basis, loss estimation is becoming increasingly important (Merz et al., 2010a; Bubeck et al., 2017). This is also recognised by the European Flood Directive (2007/60/EC) which requires the assessment and mapping of flood risk, and to draft flood risk management plans. Risk assessments aim to quantify the probability of expected losses resulting from interactions between hazard, exposure and vulnerability (e.g. de Moel et al., 2015).

Risk analyses are undertaken on different spatial scales (Meyer and Messner, 2005; de Moel et al., 2015). Our study focuses on the local or micro-scale, i.e. on the level of individual objects. These assessments are primarily undertaken to optimize investments for risk management concepts, including protection measures, urban planning, etc. Additionally, micro-scale, spatially explicit risk information enables communities, companies, and people to prepare for disasters (e.g. Takeuchi, 2001; Merz and Thieken, 2004). At the micro-scale the assessment is based on single elements at risk. For

instance, in order to estimate the loss to a community in case of a certain flood scenario, losses are calculated for each affected object, e.g. buildings. These analyses require detailed object-related data. Accurate flood modeling at high spatial and temporal resolutions remains a significant challenge (Teng, 2017). Likewise, this concerns the spatial resolution and geo-location of the exposed objects as well as object characteristics, which determine their vulnerability towards inundation. This is challenging, since such detailed data are hardly available (Apel et al., 2009).

A standard approach to determine the expected direct monetary loss to buildings are depth-damage functions based on the type or use of the building and the inundation depth (Grigg and Helweg, 1975; Smith, 1994; Penning-Rowsell et al., 2005). Accordingly, inundation depth is the variable which is most commonly included in flood loss models (Merz et al., 2010b; Gerl et al., 2016). However, making use of additional variables to explain vulnerability and to develop predictive models for loss estimation has been shown to offer substantial advancements to explain flood loss (Thieken et al., 2008; Schröter et al., 2014). The domain of flood loss modeling is experiencing a boom of tree based data analysis since Merz et al. (2013) have demonstrated the suitability and superior performance of regression trees and bagging decision trees for flood loss estimation. Also graphical models (Bayesian Networks) have been successfully applied to the domain of flood loss estimation, e.g.

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Vogel et al. (2012), Schröter et al. (2014). Decision trees have been used by Spekkers et al. (2014) to gain new insights into damage influencing factors for pluvial floods. Chinh et al. (2015), Hasanzadeh Nafari et al. (2016), and Wagenaar et al. (2017) have derived multi-variable flood loss models based on decision-tree approaches for the Mekong delta (Vietnam), Australia, and the Maas River (The Netherlands), respectively. The model validation experiment of Schröter et al. (2014) has shown that regression trees do also outperform traditional models in cross-regional and temporal transfer applications. Kreibich et al. (2017a) have proposed a novel flood loss model for meso-scale applications based on bagging decision trees which provides uncertainty information of loss estimates. In the broader context of flood hazard and flood risk assessment tree based model approaches have also been successfully applied (e.g. Wang et al., 2015; Chapi et al., 2017).

The application of multi-variable models poses high requirements on the availability of input data (Merz et al., 2013), which is particularly challenging for the spatial transfer of these models. Kreibich et al. (2017a) used empirical flood vulnerability data gathered via surveys to estimate the model input variables on municipality level. However, such data is costly and time consuming to collect and is therefore unavailable in many regions (Thieken et al., 2017; Kreibich et al., 2017b). By necessity, flood loss models are often taken from the literature and transferred in space and applied to different built environments and other settings (e.g. Balica et al., 2013). Model transfer and application is eased when data from standard databases or sources can be used because then the specification and definition of variables is similar across regions. For instance, Kreibich et al. (2010) used macro-economic data from the Federal Statistical Office Germany and the Federal Employment Agency together with geo-marketing data for the application of the multi-variable model FLEMOcs- Flood loss estimation model for the commercial sector on the meso-scale. As such, the Germany wide application of FLEMOcs was enabled. However, due to the spatially coarse data base, uncertainties in loss estimates are high. Gerl et al. (2014) examined the use of urban structure type information which is automatically derived from remote sensing data for flood loss estimation. Their analyses show that different urban structure types comprising the categories “closed block development”, “semi-open block development”, “mid-rise dwellings”, and “single-family/semi-detached houses” and the information about their specific location are valuable for flood loss modeling. However, they suggest that additional data about building characteristics which cannot be derived from remote sensing would be useful to make further advancements.

Detailed building location and characteristics can be stored in (virtual) 3D city models, which are based on CityGML. CityGML is an open standard application schema of the Geography Markup Language (GML), which represents the 3D geometry, 3D topology, semantics, and appearance of objects on different levels of detail (LOD). Hence, 3D city models provide a framework for detailed spatial information in terms of geo-located building footprints (based on cadastral data) which is useful to describe the exposure as well as detailed information about buildings characteristics and geometries which are useful to describe the vulnerability of residential buildings at risk. CityGML is the reference model for the building model in the Infrastructure for spatial information in Europe (INSPIRE; Directive, 2007/2/EC). They have been widely adopted for diverse applications in environmental simulations (Biljecki et al., 2015) including also examples from flooding and flood damage assessment (e.g. Amirebrahimi et al., 2016). However, currently building information contained in 3D city models is available for low levels of detail (LOD), i.e. LOD1 or LOD2, whereas relevant data about building openings and/or interior structures of a building are available only for high levels of detail, i.e. LOD3 or

LOD4. The concept of LODs is described in detail in section 2.2.2. Therefore, a combination with remote-sensing data might be advantageous. For instance, numerical spatial measures from remote-sensing data have been used to characterize the physical properties of landscapes (Uuemaa et al., 2009) and urban areas (e.g., Bochow, 2010; Graesser et al., 2012) and have been used as proxies for information like “socio-economic characteristics” or “energy demand” (Jensen and Cowen, 1999; Taubenböck et al., 2009).

The objective of this study is to develop multi-variable flood loss models which are based on standardized data sources to characterize the vulnerability of buildings towards flooding. We investigate the potential of virtual 3D city models and numerical spatial measures derived from remote sensing data to support the estimation of flood losses to residential buildings. Section 2 and 3 introduce the data sources and the methods applied. The results of these analyses are presented in section 4. Further, the potential of 3D city database systems to store data, embed flood loss modeling as a functional extension for risk assessment, and visualize results is explored. In this regard the prototype implementation and a case study application in the city of Dresden (Germany) are described in section 5. In section 6 the results are discussed and concluded in section 7.

2. Data

2.1. Study area

The city of Dresden (Saxony, Germany) is used as a case study for this research. Fig. 1 shows the location of Dresden along the Elbe river banks and its tributaries. In the past, floods have caused severe impacts as for instance in June 2013, April 2006 and in August 2002. The flood in August 2002 caused more than EUR 1 Bn economic damage in the city of Dresden with losses to residential buildings of EUR 305 Mn (Kreibich and Thieken, 2009).

Dresden is characterised by a heterogeneous architectural structure including historical as well as modern multi-storey buildings in the densely built-up city center, and multi-storey residential buildings as well as one-to-three-storey developments in the neighboring city districts (Gerl et al., 2014) which is the outcome of a series of eventful historic developments with drastic impacts on the building stock development such as World War II, communist planned economy and the reunion of Germany. Given this diversity of building characteristics, differences in terms of building vulnerability towards flooding are expected.

Driven by the recent floods, flood risk assessment and management is a highly relevant topic on the urban planning agenda in the city of Dresden and comprehensive flood management concepts have been put into practice (Landeshauptstadt Dresden, 2011). As part of this planning hydro-numeric simulations have been conducted to determine inundation depth maps for historic floods and for design flood scenarios. For this study, inundation depth maps for three different water levels at the gauge Dresden are available for several focus areas in Dresden. In Landeshauptstadt Dresden (2011) flood impacts have been estimated using simple flood damage curves relating inundation depth to specific loss [€/m²] for different land use classes. This damage model had been derived for the river Rhine (ICPR, 2001) and from this model the damage curve for residential buildings will be also compared to the outcomes of the flood loss models developed in this study.

Other data sources (cf. Fig. 1) are a dataset of computer aided telephone interviews (CATI) carried out after the floods August 2002 and April 2006 in Dresden (Thieken et al., 2007), building data from the 3D city model of Dresden in LOD1 and LOD2 (citydb) saved in the 3D City Database, spatial measures (SM) for the residential

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