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Damage estimation of subterranean building constructions due to groundwater inundation – the GIS-based model approach GRUWAD

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Abstract. The analysis and management of flood risk commonly focuses on surface water floods, because these types are often associated with high economic losses due to damage to buildings and settlements. The rising groundwater as a secondary effect of these floods induces additional damage, particularly in the basements of buildings. Mostly, these losses remain underestimated, because they are difficult to assess, especially for the entire building stock of flood-prone urban areas. For this purpose an appropriate methodology has been developed and lead to a groundwater damage simulation model named GRUWAD. The overall methodology combines various engineering and geoinformatic methods to calculate major damage processes by high groundwater levels. It considers a classification of buildings by building types, synthetic depth-damage functions for groundwater inundation as well as the results of a groundwater-flow model. The modular structure of this procedure can be adapted in the level of detail. Hence, the model allows damage calculations from the local to the regional scale. Among others it can be used to prepare risk maps, for ex-ante analysis of future risks, and to simulate the effects of mitigation measures. Therefore, the model is a multifarious tool for determining urban resilience with respect to high groundwater levels.

1 Introduction

The rise in economic losses due to damage to buildings and settlements resulting from flood events can be observed in recent decades. It is caused by both the increase of frequency and intensity of floods as well as the increase of flood vulnerability (e.g. Munich Re, 2010). To reduce future flood losses, an adequate risk management is required which is based on a comprehensive analysis and evaluation of risk (e.g. Schanze, 2006).

Until now, risk analyses focus on flood processes directly generated by surface water, whereas damage due to high groundwater levels as a secondary effect is mostly underestimated. However, the latter may significantly contribute to the overall flood losses. For example, 23 % of losses were caused by groundwater inundation during the flood event in 1999 in the Bern District, Switzerland (FOWG, 2004). Likewise, the flood event in August 2002 at the Elbe River affected 240 real estates of the Free State of Saxony by groundwater inundation which is about 16 % of the overall losses (Huber et al., 2003).

Furthermore, measures to reduce the risks of floods or groundwater inundation can affect each other. So, the consideration of interaction between surface water and groundwater is essential for a sound conception and planning of all measures in the risk management. It requires simulation models that can show the economic effects of the measures, based on damage assessments as a result of surface water floods and high groundwater levels. Thereby, model approaches with high spatial resolution should ensure an improved quality of the outcomes and the significance of benefit-cost analysis.

The challenges to understand and to describe groundwater inundation or groundwater flooding processes as well as their consequences are shown in Macdonald et al. (2008), Kreibich et al. (2009), Cobby et al. (2009), and Hughes et al. (2011). In addition, Kreibich and Thieken (2008) explain relevant fundamentals for damage assessment of

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groundwater inundation and the requirement of new specific loss models.

With that in mind, this paper presents a GIS[1]-based methodology of the assessment of building losses due to groundwater inundation, which has lead to the groundwater damage simulation model GRUWAD. In addition, the paper covers an overview of methodology and model design as well as first results from a case study in the city of Dresden. Thereby, the focus is on residential buildings.

2 Methodology of the damage calculation

2.1 Overall structure

The methodology was developed for calculation of building damage due to high groundwater levels. It has a modular structure. Figure 1 shows its conceptual design with three input modules and the calculation module as well as the general results of the calculation. The structure follows the Source-Pathway-Receptor-Consequence Concept (SPRC; ICE, 2001; Schanze, 2006) as a principal process generating flood risks and leads to the damage simulation model named GRUWAD. The module groundwater dynamics serves as the basis to describe the hazard in this system. Thereby, the meteorological related surface water floods and the groundwater recharge are understood as the (secondary) source as well as the groundwater flow as the (secondary) pathway. The modules urban structure and vulnerability of buildings due to groundwater inundation provide all spatial data and algorithms on the flood vulnerability considering building types and depth-damage functions as specification of the receptor. The module calculation allows GIS-based damage computing for individual buildings based on the three input modules. According to the available hydro-meteorological, hydraulic, hydro-geological and land-use data, risks as the (negative) consequences may be determined for different flood intensities and frequencies as well as for future projections of climate change and societal change. Results can be displayed in tables, diagrams and maps.

2.2 Module groundwater dynamics

The module particularly characterises the effects of a hydro-meteorological event (e.g. precipitation) on the groundwater. The event itself has an influence on the rainfall-runoff processes, surface water flow in the river system, discharge in the sewer network, and groundwater flow. The numerical determination of all these physical processes and their interactions are complex. Therefore, the analysis of the groundwater dynamics requires an adequate model approach.

Numerical possibilities are either the complex coupling of relevant simulation models or the application of a

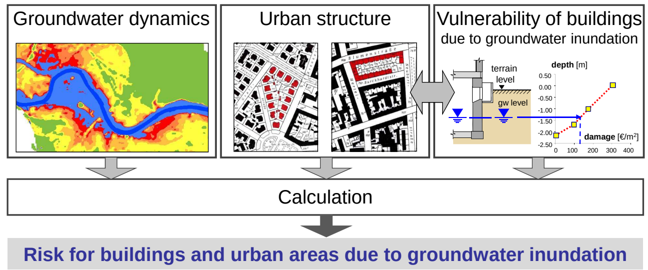

Fig. 1. General structure of the model approach GRUWAD.

groundwater flow model with qualified boundary conditions. Examples for coupled simulation systems describe Bauer et al. (2006) and Sommer et al. (2009). The latter paper includes a model system that has three models as components for the simulation of surface water, sewer water and groundwater. These coupled models aim at analysing the different physical processes in detail and the determination of the interactions between the processes. The knowledge about site-specific interactions and dominating processes as well as the emphasis of the module groundwater dynamics with its focus on determining the depths to groundwater related to the urban structure make it possible to model the groundwater flow as the main process with qualified boundary conditions. However, the quality of the outcomes is of vital importance for the choice of options. Nevertheless, the utilisation of numerical models is helpful for the derivation of scenarios and future projections. The effects of climate and other natural or anthropogenic changes as well as the effects of protection and mitigation measures can be taken into account.

The area of modelling is geared to the hydro-geological catchment area. Therefore, the area of the model should be greater than the application area of the damage calculation. On the one hand, the numeric dominated effects of boundary condition can be kept outside of the damage calculation. On the other hand, the model extend should be limited to allow for a high spatial resolution and high accuracy in the area of the damage calculation. The precision of the groundwater levels and the depth to groundwater are important because they are one crucial factor for the quality of the modelled losses.

The transient conditions of the processes and modelling indicate that the time-dependent groundwater levels are substituted by characteristic and damage relevant values. So, the parameter minimal depth to groundwater during and after a flood event is used as the transfer parameter to the calculation module. This parameter is determined by the maximum peak value of the groundwater table for every calculated finite element in the groundwater flow model. The parameter can be illustrated in synoptic maps by a specified duration during and after the flood event.

[1]GIS ... geographic information system

2.3 Module urban structure

The module comprises the aggregation of similar buildings to building types, distinguishing structure types and construction periods. The types stand for a number of buildings with similar attributes, such as size, mode of construction, spatial pattern, construction details and materials. For this reason, the same groundwater inundation is assumed to lead to similar damage to buildings of the same type. This approach is set in line with the results of damage analysis on residential buildings due to surface water flood, referred in Neubert et al. (2008), Naumann et al. (2009), and Pistrika and Jonkman (2010).

The identification of building types is based on field surveys or by an analysis of geoinformation, using the Urban-Structure-Type (UST) approach. USTs are built-up areas with a physiognomic homogeneous character marked by characteristic formation of buildings and open spaces (Pauleit and Duhme, 1999; Arlt et al., 2010). The building typology approach examines the properties of every single building with regard to the structure type and the construction period. Due to the linking of UST to the building typology, every building polygon can be allocated according to its specific building type. The reference to each building assures the high spatial resolution of the model approach over different levels of application.

The first step in this identification algorithm is the definition of the building types regarding the UST. Figure 2 shows a basic building type matrix for residential buildings in Germany. Features for differentiation of urban structure types of the residential buildings are at first, (i) detached or (ii) semi-detached and attached buildings; second, single family houses or multi unit residential buildings; and third, differentiation of multi unit residential buildings in heavy built-up blocks, blocks, linear development, meander development, large prefabricated residential development or open blocks. There are also schemes of systematisation and recording available for the non-residential buildings, e.g. buildings for industrial and commercial, sports and leisure or public facilities. The major difficulty of the systematisation is the decreased number of buildings with the same characteristic. The consequence for damage assessments is that for a decreased number of buildings the same depth-damage-function can be used by an increasing effort to determine these functions. Generally, the differentiation of USTs can be based on an interpretation of actual aerial photographs or satellite images.

The identification of building types requires additional information like historical aerial photographs or maps at different times, building statistics, building pictures from bird's-eye or street view as well as information of field surveys. With this additional information every building polygon can be allocated to a structure type and to a construction period. So, a manageable number of building types are generated as a suitable basis for the assessment of the vulnerability of buildings.

Characteristics of Urban-Structure-Types			Detached buildings (with one main entrance)				Attached and semi-detached buildings (each with one entrance)		
			single unit	multi unit			single unit	multi unit	
	Structure Types		**SF**	**MF**	**MFC**	**MFV**	**ST**	**MTO**	**MTH**
Construction period	before 1870 timber frame construction	1		MF1	MFC1			MTO1	MTH1
	before 1870 brickwork	2	SF2	MF2	MFC2	MFV2	ST2	MTO2	MTH2
	1870-1918 brickwork	3	SF3	MF3	MFC3	MFV3	ST3	MTO3	MTH3
	1919-1945 basically brickwork	4	SF4	MF4	MFC4	MFV4	ST4	MTO4	MTH4
	1946-1990 brickwork	5	SF5	MF5			ST5	MTO5	MTH5
	1970-1990 prefab. concrete building	6		MF6				MTO6	MTH6
	after 1990 basically brickwork	7	SF7	MF7	MFC7	MFV7	ST7	MTO7	MTH7

Building types

Structure types:

Detached buildings and/or free standing buildings
SF … Single unit, freestanding buildings
MF … Multi unit, freestanding buildings
MFC … Multi unit, freestanding buildings, rural building / country cottage
MFV … Multi unit, freestanding buildings, villa
Attached / semi-detached buildings, hereinafter reffered to as terraced buildings
ST … Single unit, terraced buildings
MTO … Multi unit, terraced buildings, lines and open blocks
MTH … Multi unit, terraced buildings, heavy built up blocks

Fig. 2. Basic structure of a building type matrix for residential buildings in Germany (following Neubert et al., 2008).

2.4 Module vulnerability of buildings due to groundwater inundation

The vulnerability of buildings due to floods or groundwater inundation can be assessed by depth-damage functions. Their creation requires an adequate approach for optimised results. Penning-Rowsell and Chatterton (1977), Smith (1994), Dutta et al. (2003), Merz et al. (2010) and Middelmann-Fernandes (2010) published existing ways of determining such functions by empirical and synthetical methods.

The empirical methods use existing databases of previous events. The data are used as a guiding value for the analysis of future events. One of the major difficulties are the uncertainty of the database, if the damage surveys rely upon the analysis of relief payments or insurance pay-outs (Smith, 1994).

The synthetic methods are using hypothetic analyses to estimate flood losses (Dutta et al., 2003). The advantage of this procedure is, in particular, the site-specific formulation, consistency of the calculation as well as the possible implementation of mitigation measures. Disadvantage of this procedure is the greater effort in determining the functions. As a result, in a majority of cases only the main damage types are taken into account and other types are neglected.

The specified, synthetic method used here is based on a virtual (groundwater) flooding of the receptor building in stages and an analysis of the losses for every flood step

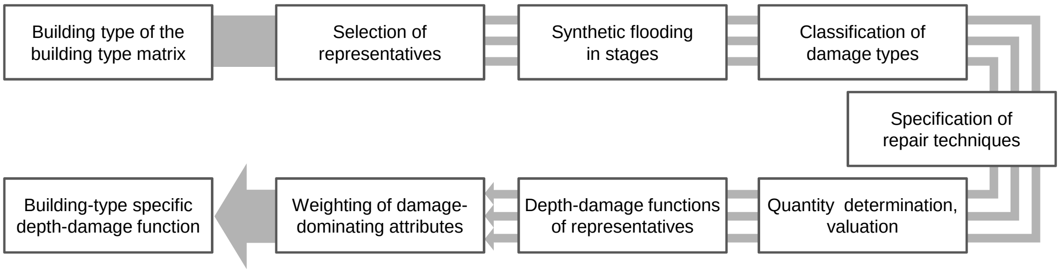

Fig. 3. Procedure to generate depth-damage functions due to groundwater inundation (Naumann et al., 2009, modified).

with help of refurbishment costs, according to Naumann et al. (2009). Figure 3 shows the applied procedure to generate depth-damage functions due to groundwater inundation. Focusing on the subterranean construction, characteristic buildings (representatives) are identified for each building type, particularly with regard to construction principles, spatial pattern, geometry, possible sealing and building services. The detailed analysis of the representatives based on floor plans, cross sections as well as detail and explanatory information. All this information is needed for the selection of the representatives and for the development of the depth-damage functions in the following steps.

In consequence of the identification procedure, the representatives stand for a building type with its typical attributes. Therefore, the damage to building construction and building services as well as the costs of refurbishment after a flood event are supposed to be similar for the same impact. However, in some cases single attributes like the ratio of basement floor area to building footprint and the foundation depth can be significantly different within the group of buildings. It is important to detect these attributes, because the properties have an essential influence on the depth-damage function of a building type. Every damage dominating attribute with a significant variation in building type requires a good representation of this attribute. If the representatives cannot be illustrated by these attributes accurately enough, one simple way to achieve this is the analysis of several representatives which differ in specific attributes. The different results of the analyses, the depth-damage functions can be weighted according to the attributes in the last step of the procedure.

The distinctive feature of the synthetic procedure are based on virtual flooding of the representatives in stages (see Fig. 4). The stages are defined by characteristic levels, where specific construction elements are affected and the building services can be attributed correctly to the respective stage. For every stage the damage patterns are characterised and refurbishment costs are calculated considering different damage types. These types are the major factor influencing the extent of losses. Three general damage types may be distinguished: (i) moisture or water respectively, (ii) structural and (iii) contamination damage. These types have different

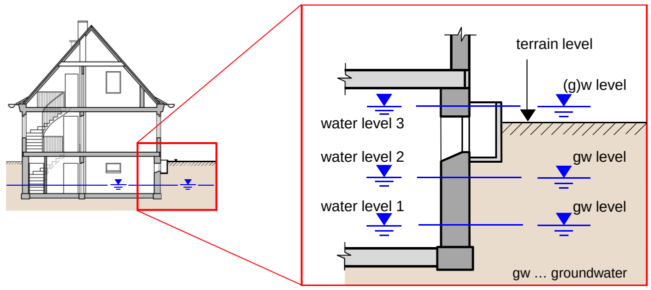

Fig. 4. Synthetic flooding in stages due to groundwater inundation.

damage patterns and thus require different repair techniques and lead to varying costs of refurbishments.

The total procedure of calculation correlates to a compressed damage expertise including the planning of refurbishments. The calculated values for the stages of flooding are the fixed points of the depth-damage function. The values between these fixed points are derived by linear interpolation for the depth-damage function of the representative.

If significant distinctions in damage dominated attributes exist, the depth-damage functions of the representatives have to be generalised for the building type. The generalisation requires specific information to these attributes, like the ratio of basement floor area to building footprint. The value of an attribute can be determined directly using the building polygon in the GIS or by statistically firm values. The first option is suitable for small case studies or adequate data supply. The second option is the typical situation: the attributes are missing in the official database, so telephone calls or face-to-face interviews are suited instruments for the determination. With knowledge of the parameter the different functions of the representatives can be weighted to the depth-damage function of a building type.

2.5 Module Calculation

This module determines the exposure of receptors, i.e. the residential buildings as a function of the respective flood scenario, and calculates the damage for every building. It integrates the parameter minimal depth to groundwater from the module Groundwater dynamics, all geodata on the building

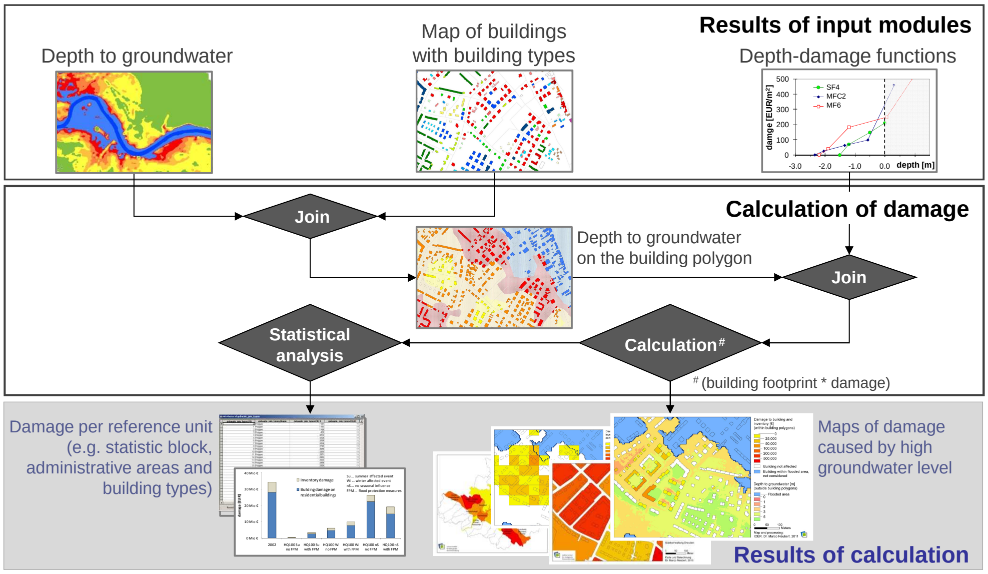

Fig. 5. Calculation of damage due to groundwater using GRUWAD.

stock with the designation of the building types from the module Urban structure as well as the depth-damage functions from the module Vulnerability of buildings due to groundwater inundation. To ensure a spatially high resolution simulation, damage is calculated on the level of individual buildings applying the building-type specific depth-damage function.

The architecture of this tool is based on the work done for the model HOWAD which calculates the damage due to river floods (Neubert et al., 2008; Neubert et al., 2012). GRUWAD as a model for groundwater damage simulation also combines the input data described above using GIS procedures (see Fig. 5). It is realised using the ArcGIS 9.3 ModelBuilder. The model follows the calculation steps listed below:

– combination of the scenario-dependent values of the minimal depth to groundwater with all buildings in the application area of the damage calculation (determining exposure);

– linking with building types and type-specific depth-damage functions, resulting in damage values per square meter depending on the groundwater table;

– object-based damage calculation;

– cartographic representation; and

– statistical analysis.

As a result of the calculation, a GIS dataset is created, which contains the potential subterranean damage to buildings caused by groundwater inundation for different scenarios, defined by the boundary conditions of the groundwater flow model. Thus, a high resolution visualisation of risk due to groundwater inundation can be derived. The damage values can be aggregated to statistical units like building blocks, urban districts or other topologies, such as raster cells or damage clusters (Veerbeek and Zevenbergen, 2009), according to the specific requirements.

3 Findings from a case study in the city of Dresden

3.1 Basic information about the case study area

The methodology and the model was performed and tested in Dresden, the capital of the Free State of Saxony, located in the east of Germany (see Fig. 6). The city is situated in the Elbe River valley and was strongly affected by the flood of the river and its tributaries in 2002. The city had a total inundation area by surface water of about 30 km^2 (LH Dresden, 2005), which is 25 % of the settlement area (Kreibich et al., 2009). Together with extreme rainfall, the interaction between the river and the groundwater was the main cause of significant rising groundwater levels. The highest groundwater levels during and after the flood event were higher than any measured before in large parts of the city area. In relation to mean flow conditions, the area with depth to groundwater below 3 m grew from around about 7 km^2 to 45 km^2 (LH Dresden, 2010).

The investigation in the case study was designed to estimate subterranean building damage due to the rising groundwater with regard to different flood scenarios and defined flood protection measures. The effects of the flood event of 2002 as well as a flood event with a 100-yr average recurrence interval (ARI) were investigated in consideration of seasonal differences of the groundwater situation. The selection of the flood protection measures were based on the “Plan

Fig. 6. Location of the study area Dresden with the Elbe River valley and its inner-city tributaries as well as the model area of the groundwater flow model (GWFM) and the application area of damage calculation; data source: ATKIS® VG250 (Administrative Borders Germany) ©Bundesamt für Kartographie und Geodäsie 2009 (Federal Agency for Cartography and Geodesy).

of flood precaution in the City of Dresden" (LH Dresden, 2010) with all realised and planned measures. The document implicates measures to prevent flooding as well as measures for limiting the rise of the groundwater table. Until now, the latter are mainly planned and realised for single and groups of historical and architectural monuments in the city centre, because of cost-intensive erection and maintenance. In summary, the results of modelling should supply damage estimates due to high groundwater levels in addition to an existing loss estimation for the flooding area.

3.2 Hydrogeological situation and groundwater modelling in the city of Dresden

The hydrogeological conditions of the investigation area are characterised by its tectonic past (Elbe River basin). The river valley covers a width of 10 km in the city area and cretaceous sediments (sandstone, limestone) are the footwall of the quaternary aquifer. Cretaceous sandstones build a lower aquifer, which was affected by extreme rainfalls in the recharge areas in August 2002. The quaternary sediments form the upper aquifer, which was also influenced by heavy rainfall and an inundation due to the Elbe flood. Gravel and sand of glaciofluvial series with less than 10 m to 60 m thickness from south to north build the main sediments of this aquifer. So, the aquifer can be seen as a uniform sediment complex because aquicludes are not widespread over the whole area of the quaternary aquifer (Sommer et al., 2009).

In the case study, the groundwater dynamics were calculated by a groundwater flow model using the software PC-GEOFIM (Sames, 2006). It is a three-dimensional, transient model with an element size of 100×100 m in the main areas as well as two inner-city mesh refinements with element size of 25×25 m and 12.5×12.5 m, respectively. The model has 10 layers. The hydrogeological situation of Dresden and the knowledge about the coupled model in the same area (Sommer et al., 2009) seem to allow a simplified modelling of flood events by a groundwater model with qualified boundary conditions.

The modelling was realised in the area of the quaternary aquifer covering about 129 km^2 (see Fig. 6). The granite complex of Lusatia in the northeast, the marine cretaceous sediments below and in the southwest border the model space. Due to the low permeability of cretaceous sediments, significant inflows to the model area can only emerge in near to surface layers.

The groundwater flow model was aimed at the description of the rising groundwater in the case of flood events of the river Elbe and its inner city tributaries (LH Dresden, 2005). The predefined water levels of the water courses correspond to the peak value of a flood event with an average recurrence interval of 100 yr (100-yr ARI). This flood event is the basis of recommended protection objective for existing settlements with adjacent buildings and also for the urban building development (LH Dresden, 2010).

Regardless of the statistically verified peak value, further influencing factors can have wide variation by a flood event, for example, the groundwater recharge and the surface water–groundwater interaction. The surface water–groundwater interaction is affected seasonal by (i) the hydrograph of the river, (ii) the percolation rate of the surface water into the groundwater as well as (iii) the groundwater levels before a flood event (initial conditions). These seasonal fluctuations as well as the conditions of flood genesis and all essential boundary conditions of the concerned groundwater reservoir were considered in a set of scenarios.

For this purpose, it was necessary to make some efforts to get qualified boundary conditions and model parameters. In this way, some additional scenarios have been developed to calibrate the seasonal average values of the boundary inflow and the groundwater recharge. As a result, wintry conditions of flood genesis were generated with a smaller increasing and decreasing hydrograph and larger flood volume. Under these wintry conditions, the percolation rate in the flooded area and the groundwater recharge are enhanced. The percolation rate is implemented in the groundwater flow model by a special boundary condition, which allows the assimilation of the inflow of surface water to the groundwater (Sames, 2006). The initial conditions were calculated by lower groundwater levels in the case of winter in comparison to the case of summer. The groundwater withdrawals are also affected by seasonal or recent hydro-meteorological conditions in addition to the main impact the fluctuation in demand.

A further criterion for the derivation of scenarios was the impact of flood protection measures, based on the "Plan of flood precaution in the City of Dresden" (LH Dresden, 2010). This plan comprised a city-wide conceptual reflection of flood precaution. It includes all protection measures, in particular also flood barriers, which are planed and realised in the city area of Dresden. All these measures are implemented in the modelled scenarios, although a part of them have not yet been realised.

Based on the analyses of the above-mentioned conditions, four scenarios have been developed:

1. A summer flood event (100-yr ARI) without flood protection measures.

2. A summer flood event (100-yr ARI) with all flood protection measures.

3. A winter flood event (100-yr ARI) without flood protection measures.

4. A winter flood event (100-yr ARI) with all flood protection measures.

Following the groundwater modelling, for each scenario a set of highest groundwater levels during and after the flood event could be found due to the analysis of the peak value of groundwater in every cell. The calculated values are interpolated in a raster of 2×2 m regarding the digital elevation model (DEM), which also has a resolution of 2×2 m. The differences between the DEM and the interpolated highest groundwater table determine the minimal depth to groundwater during and after the flood event. The resulted values are displayed in synoptic maps. In consequence of these results, Fig. 12 shows a histogram of the scenarios 2 and 4 in comparison to the flood event of 2002 relating to the spatial confinement of the damage calculation, which means the application area of damage calculation. The spatial limitation of the damage calculation area was necessary in order to keep the numeric dominated effects of boundary conditions outside.

3.3 Urban structure in the city of Dresden

The characterisation of the settlement area is based on the building footprint dataset of the Digital City Map (DSK500). From this dataset buildings with a footprint more than 30 m^2 as well as buildings with depth to groundwater less than or equal to 3 m during and after the flood event of 2002 have been selected. In total about 23 000 buildings were taken into account. For the whole study area each building was classified according to the building types defined in the first step. The attributes have been assigned directly to the polygon of each building (see Fig. 7). Attributes like structure type, construction period, building type, use of the buildings or branch of industrial/commercial building were recorded.

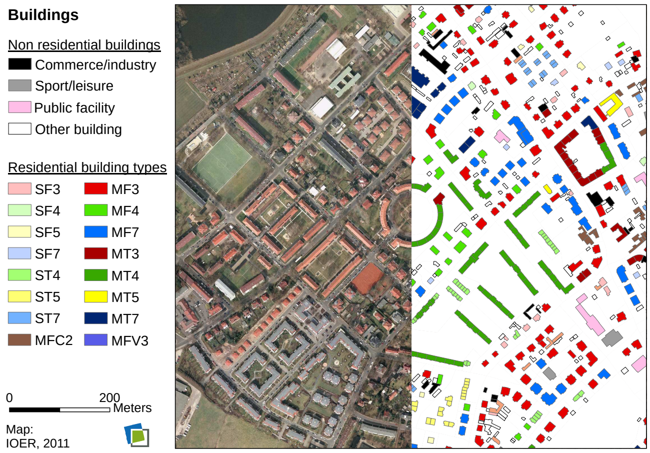

Fig. 7. Example of aerial photograph (left side) and detected building types at the river Elbe area (right side); data sources: Building layer of the Digital City Map (DSK 500), Aerial photographs 2007/2009: Dresden City Administration.

First of all, the detection and recognition of the urban structure types and the building types has been performed using on-screen physiognomic interpretation of actual aerial photographs. For identifying the construction period and building types as well as labelling the building polygons some ancillary data has been used. There are different historical aerial photographs (e.g. pan-chromatic 1953, colour-infrared 1993), historical topographic maps (e.g. Saxon mile sheets, Equidistant maps, Survey maps[2]), building age and land use plan of 1937, building statistics on basis of statistic blocks as well as address databases. Furthermore, the information about addresses and buildings on the internet was used. Especially the bird's-eye view of Bing Maps of the city of Dresden was helpful for the identification and classification of buildings by on-screen interpretation. The comparison of the various data resulted in a good accuracy of the classified construction periods. Figure 8 shows the percentage of building footprints of the residential buildings added up to the building types as a summarised result of the building type identification.

3.4 Vulnerability of buildings due to groundwater inundation in the city of Dresden

The distribution of the proportions of building footprints in Fig. 8 emphasises the different relevance of building types in the investigation area. All building types were analysed by specific depth-damage functions, if the percentage of floor area is greater than 1 %. Every relevant building type was investigated by 1 to 4 different representatives, depending on the variation of damage dominating attributes. The selection of these representatives was based on field surveys

[2]in German: Sächsische Meilenblätter, Äquidistantenkarten, Messtischblätter

Construction period		Structure Types: SF	MF	MFC	MFV	ST	MTO	MTH
before 1870 timber frame construction	1							
before 1870 brickwork	2	0,0	0,4	3,6	0,4	0,0	0,3	
1870-1918 brickwork	3	1,7	16	0,2	0,98	0,3	14	
1919-1945 basically brickwork	4	2,7	3,7		0,0	3,1	12	
1946-1990 brickwork	5	1,6	0,4			0,6	7,2	
1970-1990 prefab. concrete building	6		1,6				7,9	
after 1990 basically brickwork	7	2,5	6,8	0,1	0,0	1,6	9,5	

Fraction of building footprints differentiated by building types:

- > 5 %
- 2 - 5 %
- 1 - 2 %
- ≤1 %
- no relevance

Structure types:

Detached buildings and/or free standing buildings

SF … Single unit, freestanding buildings
MF … Multi unit, freestanding buildings
MFC … Multi unit, freestanding buildings, rural building / country cottage
MFV … Multi unit, freestanding buildings, villa

Attached / semi-detached buildings, hereinafter reffered to as terraced buildings

ST … Single unit, terraced buildings
MTO … Multi unit, terraced buildings, lines and open blocks
MTH … Multi unit, terraced buildings, heavy built up blocks

Fig. 8. Percentage of building footprints of the residential buildings added up to building types in the study area.

and the principal, engineering knowledge about the building types. The ratio of basement floor area to building footprint, the depth of foundation and the quality of basement use were identified as damage dominating attributes. These attributes cannot be illustrated with one representative accurately enough. They were taken into account individually.

The construction documents and the building plans of representatives were made available by the Dresden city archive, the regional engineering offices and the owners themselves. The plans documented the state of permit or execution planning. The documents and own inventories were used as the basis for the virtual flooding, the identification of the susceptible elements and the calculation of refurbishment costs. In this case study the damage type moisture or water damages due to groundwater inundation was considered, because this damage type was detected in the majority of cases of the flood event of 2002. In consequence of the general procedure, depth-damage functions due to groundwater inundation were derived for every representative. The generalisation of these functions to the function of building type was done based on weighting by the damage-dominating attributes.

The attribute quality of basement use can be analysed by telephone interviews. The interviews were undertaken in August and September 2007 by the SOKO-Institute, Bielefeld, Germany and first referred to in Kreibich et al. (2009). In total 605 persons of private households in the affected area were interviewed. One topic in these interviews was the characteristic of the building with the use of the basement. This information was used to derive the quality status

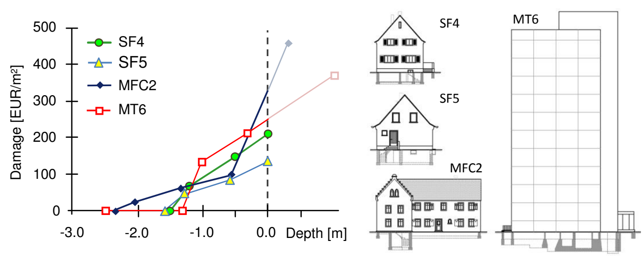

Fig. 9. Selected examples of depth-damage functions due to groundwater inundation in the city of Dresden (damage type: moisture and water damage).

of the interior construction. A distinction was made between a simple or high-quality use of the basement, which leads to a weighting factor. By the use of a quotation concerning the damage occurrence due to groundwater inundation, the interviews could not be used to determine the attribute area of foundation. Thus, the attribute was analysed primarily through a field survey and face-to-face interviews in a local district of the study area. In comparison to another study (Dekra, 2008) a comparable value can be found in the whole postal code area and it can be assumed the representativeness of the own value. The third attribute, depth of foundation, was implemented by a building type specific weighting of available data. With the knowledge of these attributes, the depth-damage functions of the representatives were generalised to the respective function of the specific building type. Figure 9 shows examples for the resulting functions.

3.5 Calculation of subterranean building losses in the city of Dresden

The calculation of losses due to groundwater inundation was carried out in the application area of the damage calculation (see Fig. 6) for residential, industrial, commercial and public buildings. Regarding the residential buildings, 18 building type specific depth-damage functions have been developed and extended by inventory functions.

From the 22 821 buildings considered, 22 141 are located within the application area of the damage calculation and classified according to their building type. Of these, 12 702 are residential buildings and 1775 non-residential buildings. The remaining 7664 buildings are identified as non-residential buildings without relevance for subterranean building losses (e.g. without basement).

The high spatial resolution of the depth to groundwater by 2×2 m is helpful for a good reproduction of the values, especially in steep terrain areas. So it is possible to assign at least one value of the depth to groundwater to each building polygon. For the determination of the groundwater-caused water level within the buildings, the depth to groundwater was spatially analysed according to building's location and building type-specific foundation depth and calculated by zonal statistics. All values within a building polygon were interpolated and the statistical values minimum, mean and maximum levels are available. For the determination of the damage, the most suitable values are the mean values, but for the calculation of the bandwidth minimum and maximum values were also calculated. So, the influence of the differences can be illustrated.

The damage calculation combined the water level per building with the building type-specific depth-damage function, based on rounded decimetre steps. For every building polygon, the building losses by refurbishment costs of building construction and building service as well as replacement values of inventory were calculated.

3.6 Results of the modelling

As a result of the calculations a GIS dataset is created which contains the potential subterranean damage to buildings caused by groundwater inundation for every affected building within the area of damage calculation per scenario. The following basic attributes are available for each building and can be displayed in maps:

- building type;
- foundation depth (m);
- groundwater inundation level (m);
- damage to buildings;
- damage to inventory; and
- overall damage (sum of damage to buildings and inventory).

All the damage values can be shown per square metre (EUR m^{-2}) or per object related to the building footprint (EUR). With a view to the attribute tables, Fig. 10 presents two general outcomes of the damage calculation for the winter flood scenario without flood protection measures. On the left side of the Fig. 10, the calculated damage is shown for every building polygon in a small part of the case study area. The depth to groundwater and the flooding areas displayed outside as well as the summation of damage to building and inventory are displayed inside of the building polygons. In this way, the damage per building allows a high resolution visualisation of groundwater inundation risk as well as an extensive spatial and statistical analysis of the results.

One possible example of aggregation shows the right side of Fig. 10. The damage is aggregated to grid cells by the affected buildings in consideration of the fraction of footprint inside the grid cells. Thus, the results can make the address and of the exact location of the damage anonymous. This is important for the protection of privacy and the publishing in official documents of administration.

With regard to the aims of the calculation, Figure 11 illustrates a comparison of the flood event of 2002 (a) and two calculated scenarios, the 100-yr ARI winter flood event without (b) and with flood protection measures (c). Figure 11 shows a map section in the southeastern part of the case study area. The boundary conditions of the different scenarios and effects of the flood protection measures are plain to see at the different flooded areas, however, without any damage values in consequence of surface water flooding. The presented damage cells contain solely the subterranean damage to buildings and inventory due to groundwater inundation. The cells located mostly nearby the flooded areas (Fig. 11a, b, c) and in the range of flood protected areas (Fig. 11c). Despite the likely reduction effect of total damage in consequence of the consideration of flood protection measures, the area of low depth to groundwater as well as the damage due to groundwater inundation can be increased. In this way, damage assessment as a part of a flood risk management system should consider also the groundwater related damage to buildings.

The view of damage due to groundwater inundation caused that the calculation results give important information outside of the flooded area. So it is obvious that the calculation provides only additional information for the evaluation of the implemented flood protection measures. However, a supplementary assessment of flood losses inside the flooded area is not available here and an interpretation about general effects of the measurements is therefore pretty difficult. A suitable way for a complementary damage calculation due to surface water floods has been presented by Neubert et al. (2008, 2012) with the damage model HOWAD. The

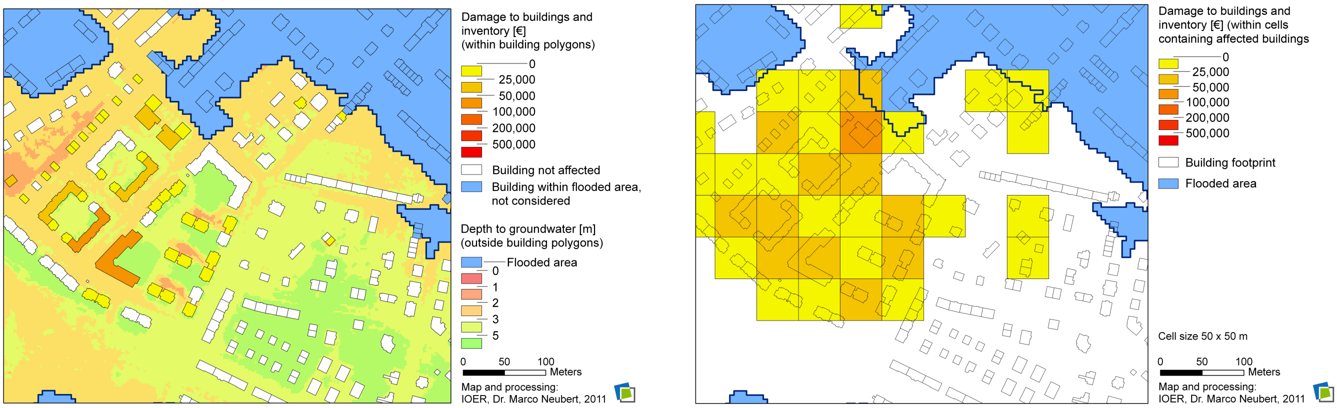

Fig. 10. Example visualisation of GRUWAD results for a subset of Dresden with the potential subterranean damage to buildings caused by groundwater inundation. 100-yr ARI winter flood scenario without the impact of flood protection measures. left side: damage to buildings and inventory within the building polygon; right side: damage to buildings and inventory summarised to grid cells (50×50 m); data sources: Building layer of the Digital City Map (DSK 500): Dresden City Administration.

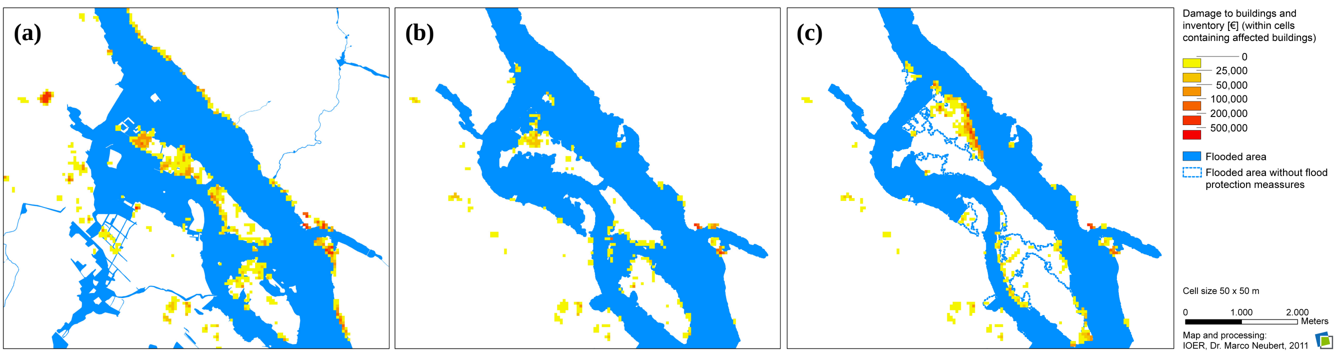

Fig. 11. Damage to buildings and inventory caused by groundwater inundation shown as damage cells for the 2002 flood event **(a)** and two 100-yr ARI winter flood scenarios **(b, c)**; **(b)**: without flood protection measures **(c)**: with flood protection measures; data sources: flooded areas: Dresden City Administration.

combination of both models is feasible because of the same architecture and the comparable level of detail.

Independent of this, the calculation of damage due to groundwater inundation makes a contribution to benefit-cost analysis of flood protection measures, especially for the measurements to reduce the rising groundwater. The strength of the new model approach is to quantify the groundwater dominated problems and the evaluation of such measures. In the case study, the measurements for limitation of the rising groundwater have only local effects for the protected buildings and the influence on neighbouring residential buildings is marginal. That is the reasons why the effects of these measures are not clearly visible in view of the whole application area.

One general, qualitative plausibility check of the damage calculation is shown in Fig. 12. The figure includes (a) a histogram with the percentage of the area divided into classes of depth to groundwater and (b) a bar chart with the overall damage for three different scenarios. Thereby, the relevant damage range are determined by depth to groundwater between 0 and 3 m. The histogram makes clear that the 2002 event has the greatest (see also Fig. 11) and both, the winter flood scenario as well as the summer flood scenario, have significant lower areas in the range relevant for damage. An adequate trend of the losses is clearly recognisable in the bar chart of the Fig. 12b. This clarifies that the depth to groundwater is a highly sensitive parameter in the damage calculation and, because of the damage calculation on building level, the GRUWAD model approach can be reflected this sensitivity.

In view of the results, it should be considered that in case of this specific issue each deep validity check and uncertainty analysis is difficult. They are missing, like in the case study, a problem-adequate and comparable database for partial and overall results. For further discussions about this, it should be noted here:

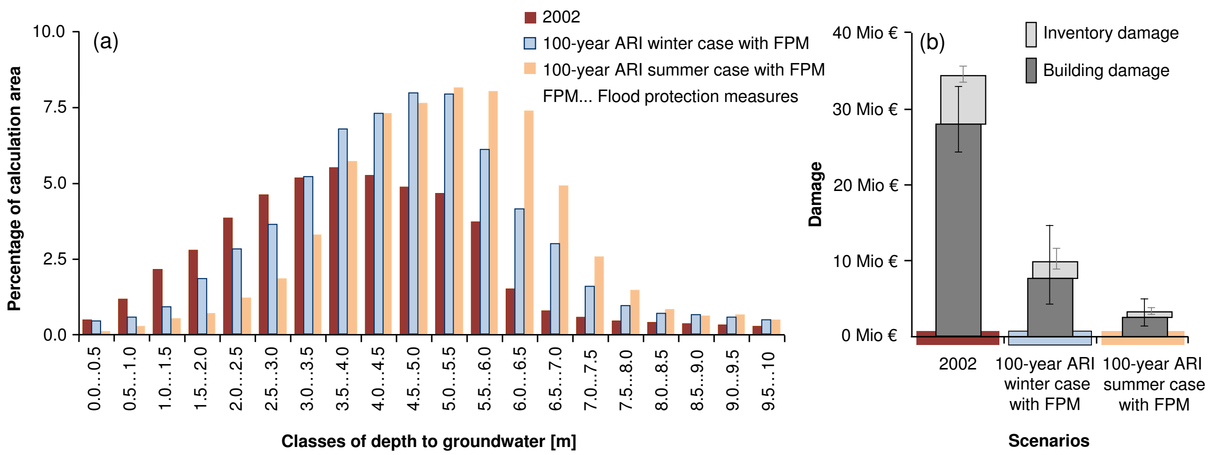

Fig. 12. Histogram of depth to groundwater classes **(a)** as well as overall subterranean residential damage to buildings and inventory caused by groundwater inundation for the ex-post analysis of the flood event of 2002 and the ex-ante analysis of winter and summer flood events with flood protection measures **(b)**.

– The availability, correctness, and extend of the database used for the input modules have an major influence of resulting uncertainties.

– The level of detail in the hydro-geological model and the uncertainty of hydro-geological parameter dataset are one essential factor for the uncertainty of modelled groundwater levels.

– The defined boundary conditions, especially with regard to the seasonal effects, determine a widespread answer for the groundwater dynamics in consequence of the same flood peak (see Fig. 12b).

– The classification of building types using geo and statistical information can be validated by field surveys.

– The vulnerability estimation with the presented synthetic methods, in consideration of adequate damage dominated attributes, reduces the uncertainty of building type specific depth-damage functions.

– A further aspect of the uncertainty is the development in construction prices as a result of the increased demand of refurbishment work after a flood event. The fact can be adapted by price indices, if such values exist.

– The range of the damage calculation themselves is illustrated in Figure 12. The error bars on the damage values symbolise the calculation with the minimum and maximum water level values of the zonal statistics for every building polygon.

These selected notes result in a range of uncertainty elements in groundwater induced loss estimation. Nevertheless, the used methods and values have provided a credible estimation for the losses due to groundwater inundation.

4 Conclusions

Until now, the subterranean damage to buildings caused by groundwater inundation as a secondary effect of flood events has been often neglected. However, the knowledge about these losses is a precondition for its integration in flood risk management and its consideration in benefit-cost analysis of mitigation measures. The paper highlights the methodology of calculating such damage to buildings with the GRUWAD model approach and a first application in the city of Dresden.

The specific feature of the model is the building object-based modelling of the subterranean damage to buildings due to groundwater inundation. This is a necessary prerequisite for a physically based modelling of the impacts (depth to groundwater) to the receptors (buildings). For this purpose, the high resolution of the calculation requires a suitable and supporting method to characterise the urban structure and the vulnerability of the building due to groundwater inundation. The combination of the building type classification and the depth-damage functions determined by a synthetic method can be assessed as suitable instruments. The transferability and the adaptability of the overall methodology to different locations is assured by the modular structure, the spatial combinations and analyses by a GIS environment as well as the adaptable derivation of site-specific building types and site-specific depth-damage function due to groundwater inundation.

The investigation of the case study Dresden serves as a basis for the first model test and focuses especially on the groundwater induced subterranean damage to buildings and the impacts of flood precaution measures. It appears that the regional scale, like here an application area of the damage calculation with about 100 km^2 and the consideration of about 23 000 buildings, are an appropriate scale for the presented methodology. The increase of the application area means especially that the effort for the manually building classification increases. The consideration of semi- or fully automatic procedures of building type identification is possible with a certain decrease of accuracy (Meinel et al., 2009). In contrast, there exist hardly limitations by smaller study areas because of the building object-based modelling.

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