Pluvial flood damage modelling

Assessment of the flood damage model HOWAD-PREVENT

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Preface

This thesis presents the research project carried out to complete the Master's program Water Management at the faculty of Civil Engineering and Geosciences of the Delft University of Technology. Two years have passed almost seamlessly, but the knowledge and skills I have gained are of immeasurable value to me.

During my studies in Delft I experienced falling with a bike on a snow but I did not experience flooding from heavy rainfall. Still, my hometown Riga was flooding – I was sitting in a Spacebox and looking at photos of Riga surrounded in water. At that moment I realized that water and the city both do go together, except the city needs help in controlling the water. Luckily, I was guided to a topic exploring the relationship of water with the city. The topic of this thesis is rainfall induced (pluvial) flood damage assessment for a study area using damage assessment model HOWAD-PREVENT. This model is evaluated for its applicability for damage assessment for small flood water levels.

I would like to express my gratitude to several people who guided me and helped me in the last 8 months of my studies. First, I would like to thank Jan Vreeburg for lifting my spirits up and giving me simple but valuable advices. Second, I would like to thank all my thesis committee members for their suggestions, comments and advices, especially Matthieu Spekkers, who supported me and reduced my worries and anxiety that came wave like. Third, I would like to thank the Druppel committee who made me think about and do other things besides my thesis work. Forth, I would like to thank my both lacrosse teams, Den Haag First Ladies and Lacrosse club Riga for being interested in my study progress and in my thesis topic thus allowing me to prepare for my final presentation by explaining what exactly I am doing. I am also grateful to Santiago Gaitan who took me by the hand and patiently led me into the ArcMap world.

I am grateful to my family who did not question my decision to go and study abroad for two years and supported me in every way they could. Finally, I would like to thank my friend Jelena who made me ask more from myself and to strive for perfection.

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Abstract

Flooding is a natural phenomenon, but human activity has significantly altered the natural drainage processes thereby occasionally causing greater flood risk. Urban flooding has become more frequent due to a number of factors including climate change with the different patterns of precipitation, urban growth and an increase in paved surfaces.

The total damage and economic cost of a past flooding event can be determined by ex-post surveying. However, flood losses can also be estimated ex-ante. For a hypothetical flood event, characterised by values for flood depth, water velocity, etc., together with a given relationship between these flood characteristics and likely damage, ex-ante flood costs can be determined. A central idea in flood damage estimation is the concept of damage curves or damage functions. Such functions give the building damage due to inundation. Most damage assessment models have in common that the direct monetary damage is obtained from the type of the element at risk and the inundation depth. The relationship between the level of inundation by floodwaters and the resulting damage to residential or commercial property is influenced by the value of the building structure, the value of its contents, and the susceptibility of each to damage.

The focus of this thesis is on pluvial flooding in urban areas. Damage assessment models do not focus solely on pluvial flood damage. Nevertheless, pluvial floods do occur in urban areas and the damage assessment related to this type of flooding is important. The present study is limited to direct monetary flood damage to residential buildings. Damage assessment model HOWAD-PEVENT is used to assess damage to a case study area in Rotterdam. The model is evaluated for its applicability to be used for pluvial flood events. In addition, the uncertainty sources are identified and quantified.

The model can be successfully used for pluvial flood damage assessment. The main uncertainty sources of the HOWAD-PREVENT are all input data sources – water level, building stock classification and depth-damage curves. While building classification has the least influence on the uncertainty, both water level and depth-damage curves have the most influence.

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1 Introduction

1.1 Background

Flooding is a natural phenomenon, but human activity has significantly altered natural drainage processes thereby occasionally causing greater flood risk. There is an increase in water runoff as less water infiltrates into the ground due to urbanisation which has reduced the permeability of land (Improvement and Development Agency, n.d.). Urban area development occurs near to or on the land where flooding naturally occurs, thus making such urban areas more prone to flooding. There is a high spatial concentration of people and values in cities, even small-scale flooding can lead to significant damage. Urban flooding has become more frequent due to a number of factors including climate change with the different patterns of precipitation, urban growth and an increase in paved surfaces.

Urban flooding can be coastal, fluvial or pluvial or even a combination of these types of floods. Coastal flooding is caused by extreme tidal conditions that occur because of high tide levels, storm surge and wave action. Fluvial flooding occurs when the capacity of a watercourse is exceeded and the water overtops its banks. Pluvial flooding takes place when the rainfall rate exceeds the capacity of storm water drains to evacuate the water and the capacity of the ground to absorb water.

Several severe flooding events have occurred in Europe over the last decades with heavy rainfall as the main cause of flood. Two exemplary events are floods in August 2004 and June 2006 in Heywood, UK (Douglas et al., 2010). The estimation of flood damage in monetary values is becoming more important as flood risk management is becoming the dominant approach to flood control policies throughout Europe. The assessment of potential damage due to flooding is of importance for several institutions, for instance water and spatial planning authorities, insurance companies and flood risk management decision-makers.

Historically, the management and mitigation of flood events has focused on fluvial flooding, with a particular emphasis on floodplain usage (Purseglove, 1988, quoted in Douglas et al., 2010). So far, considerable research has been done and progress has been made on damage data collection, data analysis and model development regarding fluvial and coastal floods (Merz et al., 2010). Very few methodologies have focused on local floods in small urban watersheds that occur due to pluvial flooding. Some reasons behind this fact are the complexity of the flooding processes in urban areas (Freni et al., 2010) and a high number of stakeholders involved.

The focus of this thesis is on pluvial flooding in urban areas. Damage assessment models do not focus solely on pluvial flood damage. Nevertheless, pluvial floods do occur in urban areas and the damage assessment related to this type of flooding is important. Although the flood volumes involved and the damage related to pluvial flooding are often not very harmful, consistent economic losses and the consequent damage can be brought upon in the long term due to the high frequency of this kind of event (Freni et al., 2010; ten Veldhuis, 2010).

The flood damage simulation model HOWAD-PREVENT used in this study was developed in Germany within the VERIS-Elbe research project by IOER[1] and was also used in the SMARTeST[2] research program. The modelling approach spatially interlinks the simulated water levels with urban structure types. Three main components form the core of this damage simulation method: (1) building type classification in a study area, (2) the development of synthetic depth-damage functions and the (3) integration of these components into the damage simulation model. The model output is a GIS data set containing the potential damage caused by flooding. The main connections (water level connection to depth-damage functions) are common to other damage assessment models. The main characteristic that makes this model different from others is the high resolution and detailed building type classification and analysis.

Rotterdam is one of the cities included in the SMARTeST research program, hence a neighbourhood in Rotterdam, Pendrecht, was chosen for the damage assessment. Rotterdam is partly built in a low-lying polder area with ground levels down to 6 meters below the sea level, from which the water is pumped out. Rotterdam is threatened not only by tidal surges from the North sea and river floods from the river Rhine, but also by pluvial floods (SMARTeST, 2012).

1.2 Relevance

Several parties are interested in the outcomes of flood damage modelling in an urban area. Stakeholders that have an interest in the flood damage quantification are those who will have to deal with flood damage or those facing the costs involved in reducing the flood risks. Each of the stakeholders might want to have different information regarding the flood damage (Messner et al., 2007) – the extent of damage, the cost, the possibilities to reduce the flood impacts, the critical flood areas etc. The stakeholders interested in the flood damage assessment and that are relevant to this study are:

- *Ministries, provincial governments and water authorities responsible for flood risk management policy*. These institutions have to justify the amount of money from tax payers that is used for flood protection. The quantifications of ex-ante flood damage estimations can show that the funds spent on flood risk management plans are beneficial to the people.
- *Municipality of a flood affected city*. After a flood event, a municipality is interested in how significant the flood was, what damage occurred and what was the total amount of loss not only for the people affected, but also for the economy. Damage estimates can be used as grounds for the distribution of compensation payments for those who have suffered from the flooding.
- *Emergency planners (fire department, police department).* Emergency planners have to know where the critical areas of flood damage are, where to concentrate action in case of emergency and which areas may have to be scarified in order to protect other areas.
- *Insurance companies.* Insurance companies are interested in their client's insured financial loss. Flood damage data is needed to assess the flood risk of properties and to specify premium levels for insurance purposes.
- *Public and private businesses, private house owners, housing corporations.* On the basis of damage calculations, private owners can decide whether it is worth taking out a flood insurance policy or spending additional money on private flood protection measures.

[1] Leibniz Institute of Ecological Urban and Regional Development, Dresden
[2] Smart Resilience Technology, Systems and Tools, EU 7th Framework Programme Environment

- *Researchers in the field of flood damage assessment.* The study conclusions can provide additional information to the existing knowledge in the flood damage assessment field.

1.3 Objective

This study is carried out with the main objective to test the flood damage assessment model HOWAD-PREVENT in a case study in Rotterdam and to evaluate the uncertainty and sensitivity of this model.

General aims regarding the study are:

1. Literature review regarding flood damage modelling in order to learn about the concepts used in damage modelling and to find the model uncertainty sources;
2. Detailed input data review and model uncertainty and sensitivity assessment as well as evaluation of uncertainty influence on model outcomes;
3. Suggestions for model improvements and adjustments.

1.4 Research questions

The following research questions have been proposed for this study:

1. What is the current state of research in flood damage modelling?
2. What are the main uncertainty sources in the damage models developed up until now?
3. Which of the uncertainty sources have been analysed and what are the knowledge gaps?
4. What are the main uncertainty sources in the damage model HOWAD-PREVENT?
5. Are the existing depth-damage curves developed for HOWAD-PREVENT model applicable to small flood depths?
6. To what extend does the assessment outcome differ, if one averaged depth-damage function is used instead of a variety of functions for each building?

1.5 Research methods

The research questions proposed in paragraph 1.4 will be answered using the following methods: questions No. 1, 2 and 3 will be answered by thorough literature review, questions No. 4, 5 and 6 will be answered by analysing the model and applying it to a case study area. The uncertainty and sensitivity analysis of HOWAD-PREVENT will be performed by applying three water level combinations together with two building type combinations.

1.6 Thesis outline

Chapter 2 is dedicated to the literature review answering the first two research questions. Chapter 3 continues the literature review and provides an overview of the uncertainty sources found in damage assessment models. Chapter 4 deals with the materials and methods used in this study describing the pluvial flooding context, the study area and the damage assessment model HOWAD-PREVENT providing answers to the research question No. 3. Chapter 5 presents the modelling results and answers research question No. 4. Research questions No. 5 and 6 are answered in Chapter 6, which also provides the final conclusions and recommendations.

2 Literature review

This chapter presents the literature review and provides the basic information regarding flooding – flood types, flood damage types, classification of elements at risk during a flood, main damage estimation approaches, flood actions on buildings and a brief summary of the damage assessment models developed up until now.

2.1 Flood types

Flooding derives from the natural processes of heavy rain, tidal surges and raised groundwater levels. It can also result from interference with the natural drainage processes, such as changes to river channels, increased runoff from land or blocked sewerage systems and culverts. In extreme weather conditions, rivers, streams and drainage systems reach their capacity and the ground becomes saturated. The boundaries, for example embankments and pipes, can no longer retain the water that has been gathering and this in turn leads to the bank overflow. This overflowing water follows the path of least resistance, settling in low-lying areas. Human activity frequently acts as a flood intensifying factor by modifying key hydrological variables such as water storage and infiltration (Smith & Ward, 1998).

There are four broad flooding categories:

- Coastal flooding,
- Groundwater flooding,
- River (or fluvial) flooding,
- Pluvial flooding.

Coastal floods occur in low-lying coastal areas, including estuaries and deltas, when the land is inundated by brackish or saline water. Brackish-water floods result when river water overspills embankments in coastal reaches. This overspill can be intensified when high-tide levels in the sea are increased above the normal level by storm-surge conditions or when large freshwater flood flows are moving down an estuary. Saline water coastal floods may occur when extremely large wind-generated waves are driven into semi-enclosed bays during severe storm (Smith & Ward, 1998).

Problems with high groundwater levels mainly occur in floodplains or low-lying areas. Damage due to high groundwater levels occurs if there is a considerable (sudden or long-term) change in the groundwater levels. Such changes can be a result of high infiltration rates (due to flooding or heavy precipitation) into the aquifer or a reduced withdrawal of groundwater (Kreibich & Thieken, 2008).

Floods in river valleys occur mostly on floodplains as a result of flow exceeding the capacity of the stream channels and overspilling the banks. Most river floods result directly or indirectly from climatological events such as excessively heavy and/or prolonged rainfall (Smith & Ward, 1998).

Pluvial flooding results from heavy rainfall when water that does not infiltrate into the ground, ponds in natural or artificial hollows or flows over the ground before it enters a drainage system or watercourse. Pluvial flooding is typically associated with short duration high intensity rainfall, but can also occur with lower intensity prolonged rainfall. The pluvial flood extent can be worsened if the ground is saturated, frozen, paved or otherwise has low water permeability (Falconer, 2009).

2.2 Flood damage types

Flood damage is mostly categorised firstly in direct and indirect damage and secondly in tangible and intangible damage (Parker & Green, 1987).

2.2.1 Direct/indirect damage

Direct flood damage occurs immediately after the event as a result of the physical contact of the floodwaters with humans and with damageable property. Indirect flood damage is equally or even more important despite the fact that this damage is less easily connected to the flood disaster and often operates on long time-scales (Smith & Ward, 1998). In general, the costs of direct impacts are easier to quantify than indirect costs. One of the reasons is that indirect damage may have an effect lasting from months to years (Merz et al., 2011). In extreme events, indirect losses may exceed direct losses (Penning-Rowsell & Fordham, 1994).

2.2.2 Tangible/intangible damage

Tangible damage is damage to a manmade capital or resources that can be valued in monetary terms. Intangible damage is damage to assets and people that are not normally bought and sold and for which market values do not exist (Handmer, 1986; Messner et al., 2007).

Assessment of direct tangible loss is relatively straightforward. Such losses are often the most visible, and both researchers and government authorities have devoted most attention to the assessment of direct damage. Indirect intangible losses are the most difficult of all to identify and are often ignored or clouded in the damage assessment process (Handmer, 1986).

Table 2.1 presents the flood damage category matrix with examples of each damage type. If possible, flood risk assessment should comprise all damage types in order to obtain a complete damage extent. However, damage analyses are frequently limited only to direct economic losses, mostly because the available methods do not derive reliable statements regarding other loss types (Merz et al., 2011).

Table 2.1 Flood damage types (adapted from Merz et al., 2011; Smith & Ward, 1998)

	Tangible	*Intangible*
Direct	Physical damage to assets: buildings and contents Destruction of infrastructure Erosion of agricultural soil Destruction of harvest Damage to livestock Evacuation and rescue measures Business interruption inside the flooded area Clean up costs	Loss of life (mortality) Health effects, injuries, distress (morbidity) Damage to cultural heritage Negative effects on ecosystems

Table 2.1 Continued

Indirect	Disruption of public services outside flooded area Production losses to companies outside flooded area Cost of traffic disruption Loss of tax revenue due to migration of companies in the aftermath of floods Temporary rehousing	Inconvenience of post-flood recovery Increased vulnerability of survivors Loss of trust in authorities

2.3 Applications

The flood damage assessment can be used for the following applications (Merz et al., 2010):

- *Determination of elements at risk in flood prone areas.* The elements vulnerable to flood are not only the tangible ones like buildings, appliances, vehicles, but also whole communities.
- *Flood risk mapping.* Flood damage risk maps show the spatial distribution of the damage risk. Typically, the maps are based on a number of synthetic events with different exceedence probability. The flood risk maps are used for raising awareness among people at risk and decision makers as well as for providing information for land-use planning and urban development. Validation of flood maps is usually difficult and such maps are expected to be uncertain (Merz et al., 2007).
- *Optimal decisions on the funding use for flood reduction measures.* Cost-benefit analyses have to be performed to evaluate and compare different flood reduction measures. The safety measures against floods require a vast amount of funding, which comes from tax payers, therefore optimal decisions are essential.
- *Comparative risk analysis.* A municipality may be subjected to various natural hazard types, for example flooding, earthquakes, storms, extreme temperature changes, volcanic eruptions and other potential hazards (EEA, 2010), therefore flood risk mitigation measures have to compete with other fields that are dealing with risk reduction. A quantitative comparison of these different risks can be done based on damage and risk estimates (Grünhal et al., 2006, quoted in Merz et al., 2010).

2.4 Spatial scales

The flood damage assessment can be performed on different spatial scales (Merz et al., 2010; Messner et al., 2007):

- *Macro scale.* Includes large spatial units, typically administrative units, such as municipalities, regions and even countries. National and international studies may refer to a national coastline or a river basin of a transboundary river.
- *Meso scale.* Includes medium size units and is based on spatial aggregations, which in general are land use units, for instance residential or industrial areas. These are also administrative units, for example a postal code area[3].
- *Micro scale.* Includes small, local units and the assessment is based on a single element at risk – building, infrastructure object, etc. Micro scale approach requires detailed input data

[3] In the Netherlands, a 6 digit postcode is 30 households.

and large effort per unit area. At micro scale data is often object oriented (a building is a point or polygon with attributes).

- *Pico scale.* Includes even more detailed level than the polygon or point data. The cells can be as small as 0,5x0,5 m. This allows even more accurate calculations than micro scale (for example it is possible to locate the entrance to a building and the orientation of the street to see, whether the house floods or not) (Hoes O., pers. com.).

The classification in micro, meso and macro scales is related not only to the size of the study area, but also to the assessment method and the level of aggregation. The most detailed methods are usually restricted to local size areas, but studies for regional or national size rely on approaches that use less effort per unit of area and therefore the provided degree of precision is lower (Messner et al., 2007). **Error! Reference source not found.** depicts this statement raphically.

Another reason for the division of spatial scale is the differentiation between economic and financial losses. For the loss to be considered an economic loss, it must affect the economy of the region that is included in the damage assessment, e.g. nation. Financial losses are losses experienced by an individual enterprise – besides direct damage, financial losses include any business lost to a competitor (either temporarily or permanently) as a consequence of flooding (Handmer, 1986).

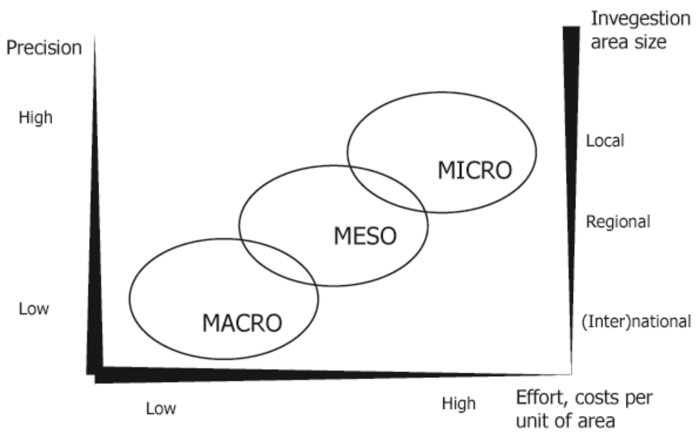

Figure 2.1 Damage assessment method scale levels (Meyer, 2001, in Messner et al., 2007)

2.5. Classification of elements at risk

Vulnerability is a system characteristic describing its potential to be harmed. Vulnerability can be considered as a combination of susceptibility and value. Susceptibility is a tendency of a particular receptor to experience harm (Gouldby et al., 2005).

Vulnerability and possible damage varies between elements at risk in a study area. In most cases it is not possible to assess the damage for each single object separately, since there is no information on the susceptibility to floods for each object and such detailed assessment would require great effort. As a result, elements at risk are classified and unified into groups having one or more distinctive characteristics. All elements within one class are treated in the same way. For example, households of a certain type can be grouped in one class and may obtain the same asset value related to the floor area. The classification mainly depends on the data availability and is based on various economic sectors: private households, industry, companies, public sector, infrastructure, agriculture and others (clean-up costs, evacuation and disaster management costs).

For sectors with limited data availability, simple assessment approaches are applied, while sectors having sufficient data use more detailed approaches (Merz et al., 2010, 2011).

One of the elements at risk receives more attention in this study – private households. Regarding building classification, some damage assessment methods establish subclasses. One example is building classification using building's structural characteristics (Schwarz & Maiwald, 2008). Another approach is presented by Thieken et al. (2008) – buildings are classified based on building type (single-family house, (semi-)detached house and multi-family house) and quality (low, medium or high).

2.5 Damage influencing factors

2.5.1 Impact and resistance factors

The damage severity of an object is determined by the combination of flood impact and object resistance. Flood impact parameters depend on the nature and size of the flood. Object resistance parameters depend on the flood prone objects' characteristics and represent the capability or incapability for the object to resist the flood impact. Table 2.2 gives an overview of the damage influencing factors. Most of these damage influencing factors are neglected in the damage modelling due to their heterogeneity in space and time, difficulty in prediction and limited information on their effects (Elmer et al., 2010; Thieken et al., 2005).

Together with the object type, water level it is the most frequently used impact parameter in damage evaluation. In addition, the depth of flooding is generally the most critical variable for urban flooding (Penning-Rowsell & Fordham, 1994). Based on the assumption that water level has the strongest influence on damage magnitude, most of the damage functions are water depth-damage functions (Messner et al., 2007). Handmer (1986) states that flood duration is generally not important for urban flooding damage assessment.

Table 2.2 Damage influencing flood factors (adapted from Merz et al., 2010)

Parameter	Description
	Impact parameters
Inundation depth	The higher the inundation depth, the greater the building and contents parts which are damaged, also the stronger the buoyancy force.
Inundation duration	The longer the inundation duration, the greater the buildings' and contents saturation with water, the higher effort for drying.
Flow velocity	The greater the flood water velocity, the greater the probability of structural building damage due to lateral pressure, scouring etc.
Contamination	The greater the contaminant amount, the greater the damage and the cleaning costs. Inclusion or adsorption of contaminants may lead to total damage (inclusion of small particles in porous material is impossible to remove; dispersal of microorganisms in moist building material requires extensive cleaning and disinfection).
Debris/ sediments	The presence of debris in floodwater, depending on amount, size and weight, increases the dynamic forces which affect buildings and thus increases the potential for structural damage. Sediment can damage floors and mechanical equipment and may lead to an increased effort for cleaning up.
Inundation frequency	Repeated flooding may have cumulative effects, increasing the probability of damage. At the same time, preparedness significantly increases, leading to reduced damage.
Timing of flood event	Night – can be associated with greater damage due to ineffective warning distribution. Holidays – the property owners might be absent and thus unable to act to reduce damage.

Table 2.2 Continued

Resistance parameters	
Building use /business sector	Significant difference between sectors with regard to the exposed assets and susceptibility.
Building type	Multi-storey buildings have advantage over single-storey buildings due to their weight and resistance to buoyancy force.
Building material	Different building materials react differently to water exposure. Additionally, material drying and decontamination can be more or less difficult. Building materials affect the weight of a building and thus the danger of buoyancy.
Precaution	Various precautionary measures can reduce the flood damage significantly, for example constructional measures (elevated building, suitable building material) and flood safe storage.
External response/ emergency measures	Emergency measures can be applied effectively with sufficient warning time and low water levels. Such emergency measures are the dismounting of fixed equipment/machinery, relocation of inventory, sealing of openings to prevent water from entering the building.
Early warning	Emergency measures can be undertaken efficiently, if the warning time is sufficiently long.

2.5.2 Flood actions on buildings

Flood actions described in the following paragraphs are the acts which a flood could do directly to a building, potentially causing damage. Direct damage to buildings occurs due to forces, pressure, chemical reactions, energy transfer and other impacts. While all these action could be present during a flood, most of the damage assessment methods take into account only the inundation depth.

This paragraph is based on the work from Kelman & Spence (2004).

2.5.2.1 Hydrostatic, hydrodynamic actions and buoyancy

Hydrostatic actions

(1) Lateral pressure. The lateral pressure results from differences in interior and exterior water surface elevations. The lateral pressure imposed against a building may be considered for the entire building or for only a part of it, for example to a glass window or a timber door. Sufficient lateral pressures may cause permanent deflections and damage to structural elements within the building. A "leaky" building would have a low potential for damage, once the water leaks inside and reaches the same level as the outside, thus eliminating the lateral force.

(2) Capillary rise. Capillary rise can cause damage higher than the level that flood water has contacted the building's components.

Hydrodynamic actions

Hydrodynamic actions are grouped in five groups: three of the actions are related to velocity and two are related to waves:

(1) Lateral pressure represents the dynamic pressure due to the steady flow of fluid. This pressure occurs at the stagnation point of a fluid flowing around a body.

(2) Localised changes in velocity and therefore in pressure difference occur, when water flows around corners, around a building or through gaps.

(3) Turbulence is irregular fluctuations in water velocity which can consider one or both the magnitude and the direction of water resulting in eddies, vortices and gusts. Turbulence can be highly variable over short spatial and temporal scales.

(4) The peaks and troughs of non-breaking waves can increase and decrease the pressures and the total force applied on a building. The exact change in total force depends on the ration of wave height to water depth.

(5) Waves breaking in, over, through or near a building, can convey large pressures when compared with other hydrodynamic actions.

Buoyancy

The buoyant forces are the vertical uplift of the structure due to the displacement of water. When the buoyant forces exceed the weight of the building components and the connections to the foundation, the structure may float from its foundation. The floating building or parts of the building can be displaced by hydrodynamic actions or the lateral pressure causing damage and destabilisation.

2.5.2.2 Erosion and debris actions

Erosion is caused by moving water that scours away soil. The erosion mechanisms are lift and drag forces; turbulence may produce instantaneous upward forces that can be large enough to cause entrainment. If solids are the major part of a flood wave, the flow is no longer considered to be a water flood. The forms of debris actions can be classified into three groups: static actions, dynamic actions and erosion. Static debris actions would occur due to sediment accumulating outside or inside of the building. Dynamic actions would occur when debris moved by water, impacts a building. Impacts can come from outside (e.g. timber logs, bins, pebbles) or inside (e.g. furniture) of the house. Erosion is caused when household items or pebbles are being dragged along with the flow of water scraping out soil from the sides or bed of the flow channel.

2.5.2.3 Non-physical actions

There are two non-physical flood action forms: chemical and biological actions. Chemical actions occur when water contacts an object; these actions may corrode materials such as brickwork, glass, timber or PVC[4]. Flood water can be contaminated with sewage, oil, petrol, paint and with household or industrial chemicals. Physical parameters, such as flood water pressure and temperature, influence the rates and consequences of chemical reactions, for example, explosions. Biological actions include microorganisms which thrive in damp conditions, particularly moulds and fungi.

2.6 Flood damage estimation approaches

Flood loss estimation is typically a data-intensive exercise. The following paragraphs describe data sources that are used in flood damage assessments and the assessment concepts. The data sources include survey data, insurance claim data and depth-damage curves. Damage assessment model concepts employ three main approaches: empirical approach, synthetic approach and a combination of both empirical and synthetic approaches.

2.6.1 Empirical approach

Empirical approach utilizes damage data collected via polls or by building surveyors after flood events, where a substantial number of properties have been involved. Empirical data contains

[4] Polyvinyl chloride - plastic

the actual damage. These are real losses experienced at one point in time, given the community's preparedness, length of warning time and other specific circumstances. The fact that the collected values are values for a specific, unique event can have a negative impact on future damage assessments for which these values will be used. These specific event damage estimates have to be scaled up or scaled down for larger or smaller scale floods or used for another moment of time proving the transferability in time and space difficult. Another shortcoming of empirical approach is that not always the surveys regarding damage are based on the exact same surveying method, therefore the dataset might not be homogeneous (Handmer, 1986; Messner et al., 2007).

Surveying allows collecting information with controlled data quality, if careful questioning is provided. Survey questions should be designed with the variable (or variables) of interest in mind. When surveying people who have experienced flooding, questions regarding the asset loss should be supplemented with questions aiming to determine the remaining useful life of those assets. If this is not done, the value of the lost asset will be overestimated – respondents will state the value of a brand new equivalent and not the value of asset given its age. Surveying should be done at a time when the flood event and its impacts can be still accurately recalled by the flood victims (Walton et al., 2004).

The most accurate survey data can be obtained by careful sample design, questionnaire layout and wording of questions. Ideally, surveying should be done including the entire affected population. Respondent participation can be enhanced, if a survey method combination is used: questionnaires, face to face interviews, telephone interviews and community focus groups. Method mixing can also be used to validate the survey results. A surveying disadvantage is the cost and time investments – if these are limited, the required level of detail and coverage might not be met (Walton et al., 2004).

Another information source is insurance claim databases. While surveying takes a lot of time and effort, insurance companies have aggregated claim information for the flood events stored in databases (Walton, 2004). One of the drawbacks of these databases is that the access to insurance claim data is often difficult, since not all of the insurance companies or insurance associations choose to publish their databases most likely due to the privacy protection reasons (Busch, 2008). In addition, the data classification is not always clear – there is no distinction between drinking water supply pipe bursts, roof or window leakage and the overland flow flooding (ten Veldhuis, personal communication). Another drawback is that insurance data can exaggerate the true value of loss, since household contents insurance policies typically offer full replacement of many items, regardless of their age (Walton et al., 2004).

2.6.2 Synthetic approach

Synthetic approach employs damage data collected using "what if" questions (for example, what would be the loss, if the water depth was 1 meter?) and the damage is estimated for standardised, typical property types and not for actual properties. The major advantage of this approach is that the flood damage can be calculated for any flood in any area, which is valuable for areas where no floods have occurred previously and the empirical data is not available (Handmer, 1986; Merz et al., 2010).

In contrast with the empirical approach, the synthetic assessment results in potential damage and no account is taken of warning time, population preparedness, emergency actions or the variability of characteristics within property type. Therefore, a major issue in the synthetic approach is the conversion of potential damage into actual damage (damage that might be reasonably expected). Another disadvantage of the synthetic approach is that by being a standardized methodology, it is only an approximation of local conditions (Handmer, 1986).

2.6.3 Asset value estimation

Both synthetic and empirical approach requires asset value estimation for all flood affected objects. The total asset value is necessary in case relative damage curves are used (see the following chapter). Within one type of objects at risk, sub-categories can be identified, for instance, a residential house has the value of the building itself (fixed assets) and the value of its contents (moveable items). The flood susceptibility varies for both categories – fixed assets cannot be moved from the flooded area while moveable items can be protected by moving to dry places. Additionally, both categories contribute to the total asset value with different proportions, therefore the estimates for both sub-categories should be carried out separately and summed afterwards (Merz et al., 2010).

Objects at risk usually are grouped and the damage assessment is performed for the whole group. The object grouping has to be done as homogeneously as possible, so that distinct curves can be constructed for each object type. Usually, the values of assets are available on a coarse level, such as the level of a municipality (Seifert et al., 2006, quoted in Merz et al., 2010) or a census block. For the damage assessment, these coarse values have to be disaggregated to use them at a lower spatial level. In several studies different disaggregation methods have been developed that use additional information sources for the disaggregation. Topographic maps, traffic networks, satellite or land use data sets have been proved suitable for this purpose (Merz et al., 2010).

As stated in Merz et al., (2011), there are not many risk assessment studies that explicitly explain approaches for the asset estimation. Some examples are German damage assessment method MURL, where the value of residential buildings has been estimated by multiplying the number of buildings with their mean insurance value (MURL (2000), quoted in Merz et al., 2011). Kleist et al. ((2006), quoted in Merz et al., 2011) has used a methodology that links available information on standardised construction costs for residential buildings with census data about the building stock and the living area per community. In USA, HAZUS-MH model has used building occupancy types which to a certain degree reflect the economic activity of the occupants. Then, multiplying the total floor area of a building with the building replacement cost (per m^2), results in a building asset value for the specific building occupancy type (Merz et al., 2011).

2.6.4 Depth-damage curves

The most important concept in flood damage estimation is damage curves[5], which predicts the monetary value of the loss if a particular building class is flooded to a particular depth and expresses this loss either per property or per unit area of such property (Penning-Rowsell & Fordham, 1994, Penning-Rowsell & Chatterton, 1977). The depth-damage curve approach has been proposed in USA (White, 1945, 1964, quoted in Merz et al., 2010) and is accepted as the standard approach in flood damage assessment in urban areas (Smith, 1994, quoted in Merz et al., 2010). Depth-damage curves enable extrapolation of empirical damage estimates to different flood heights and are essential to synthetic damage assessments (Handmer, 1986; Merz et al., 2010).

Synthetic depth-damage curves are created, when specific losses are assessed by expert assessors for pre-defined inundation levels. A sum of money is allocated in case of absolute curves

[5] Various authors use both terms – curves and functions. Reviewing the literature, it was noticed that a curve is not always called a curve and a function is not called a function. In this thesis, both terms will be used separately: a depth-damage curve is a curve that has been made empirically or synthetically by using known water depths and the corresponding fraction of damage or amount of money for replacement. A depth-damage function is a function that links the damages with water level and is expressed as a formula.

and a fraction of the total building loss is allocated in case of relative curves. The values in between the known points are interpolated. Empirical curves are created based on the information of known inundation levels and the corresponding damage costs (Penning-Rowsell & Fordham, 1994).

Depth-damage curves are most applicable to residences, where properties can be more easily categorised according to value, number of floors, construction materials etc. For the commercial and industrial buildings, these curves are less practicable due to the fact that content and construction of these buildings varies to a high extent (Merz et al., 2010).

Absolute and relative loss curves

There are two damage curve types – relative and absolute curves. In order to employ the relative curves, at first the total value of elements at risk have to be found. Then the damage is calculated with relative curves which show the damaged share of the total value to inundation depth. The loss ratio is multiplied with the total asset value to derive the absolute object loss (Messner et al., 2007).

Absolute loss curves estimate the loss directly in monetary units and there is no need to determine the total asset value of the objects at risk. The absolute curves show the absolute amount of damage depending on the inundation depth (Messner et al., 2007).

Examples of both curve types are given in Figure 2.2 and Table 2.3 shows absolute and relative loss curve advantages and disadvantages.

Table 2.3 Advantages and disadvantages of relative and absolute damage curves (Merz et al., 2010)

Type	Advantages	Disadvantages
Absolute	Total object asset values are not needed	Need for regular database update OR the curves have to be created for the particular study area Curves are dependent on the building type (or asset considered)
Relative	Independent from asset values Easy to transfer to other study regions Simple, if property value data sources are available Better transferability in space and time	Total object asset values are necessary

Besides damage curves, damage functions are used for the damage assessment. Both Apel et al. (2008) and Ernst et al. (2008) use a simple relative function that has been used in different flood risk mapping projects in Germany (ICPR[6] (2001), LfUG[7] (2005), quoted in Apel et al. (2008)): $\mathrm{y} = 2\mathrm{x}^2 + 2\mathrm{x}$, where y is the damage factor and x is the water level (in m). First, the function is combined with the estimation of inundation depths per land cover unit or per building in order to determine damage factors. The damage factors are then multiplied by the total asset value assigned to each land cover unit or building.

A simple damage function has been used in "Hoogwaternormering regionale watersystemen" (2000) assessing pluvial flood damage in the Netherlands after flooding events in the autumns of 1998. The damage in an urban area (residential and commercial) is calculated by the damage factor multiplying the maximum damages per hectare:

$$f(h, \Delta t) = \min\,(0{,}01 + h, 1).$$

[6] International Commission for the Protection of the Rhine
[7] Saxon State Agency for Environment and Geology (Sachsisches Landesamt für Umwelt und Geologie)

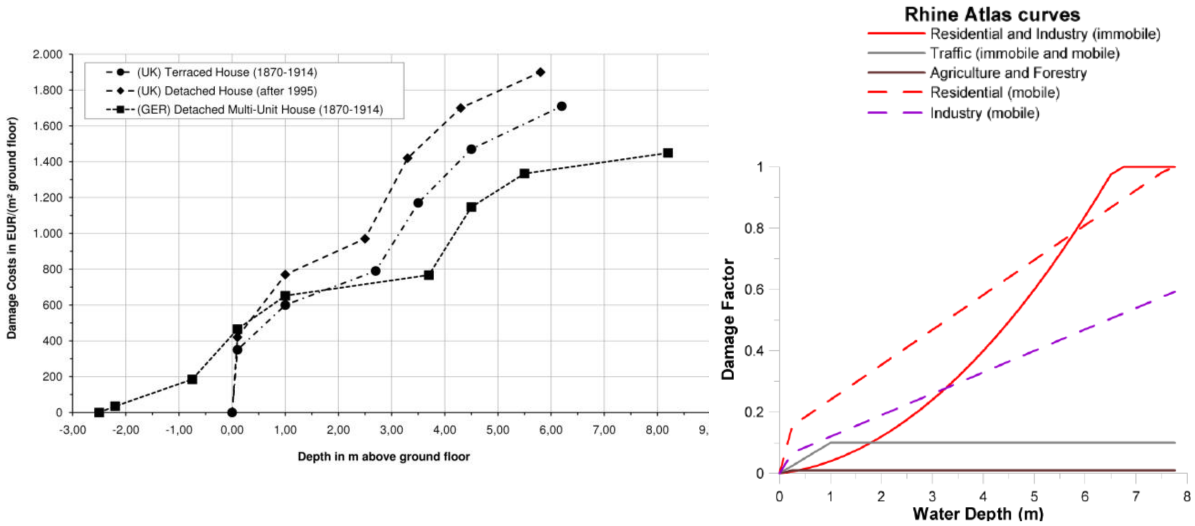

Figure 2.2 Example of absolute depth-damage curves (left) (SMARTeST deliverable D4.1, 2012) and relative depth-damage curves (right) from Rhine Atlas (de Moel & Aerts, 2011), both have been developed for fluvial flood damage assessment

2.6.5 Damage data availability and reliability

Information regarding floods, their extent, damage and costs is necessary not only to create empirical damage assessment methods but also for model validation. As already discussed in paragraph 2.6.1, this information is stored in databases. An example of flood damage database is the empirical German HOWAS21[8] database, held at the Bavarian Water Management Agency in Munich. HOWAS21 currently holds information regarding approx. 6000 claims, half of these entries concern private households, 2400 are trade and industry and a small part is traffic disruption information. The damage values in HOWAS database have been estimated by damage surveyors. Each HOWAS data set contains information about the following attributes: sector, damage, water level, flood event, location and data collection method. Damage to buildings is accounted as restoration costs, while damages concerning inventory are viewed as replacement costs (Merz et al., 2004).

A synthetically generated database is the Multi-Coloured Manual in the UK provided by the Flood Hazard Research Centre (FHRC) from Middlesex University (Penning-Rowsell & Chatterton, 1977, Penning-Rowsell et al., 2003, in Messner, 2007). The database provides depth-damage functions for 100 residential and around 10 non-residential property types. The functions for residential buildings are created synthetically in four steps: (1) definition of a standard property type and inventory, (2) monetary value determination for the standard property building materials and inventory, (3) expert assessor estimation of the susceptibility of each item to inundation depth, (4) depth-damage function construction. For non-residential properties, surveys are carried out asking the responsible persons of a company about the value of assets at risk and about the susceptibility of these assets to inundation depth. Both residential and non-residential functions also take into account the inundation duration (less than 12 h and more than 12 h).

The damage assessment by surveyors is exposed to variation and these assessments are subjective. There are observations that reveal damage data quality problems, for example, shortly after the severe flood event in Germany in August 2002, the total flood damage was estimated to

[8] http://nadine-ws.gfz-potsdam.de:8080/howasPortal/client/start

be more than 22 billion euro. This amount was corrected to about 9 billion euro in December 2002 while the actual repair costs amounted to a total sum of 11.6 billion euro (Merz et al., 2010).

There are a few studies that analyze and compare flood damage data sets, for example Downton & Pielke (2005). Their analyses reveal that the accuracy of the damage data depends on the scale of the flood and/or on the level of aggregation: individual damage estimates for small events tend to be extremely inaccurate and damage estimates become proportionally more accurate at higher levels of aggregation.

An example of insurance database is given in Spekkers (forthcoming). In the Netherlands, nearly everyone is insured for water-related damages through their property and content insurance. The Dutch Association of Insurers has compiled a database containing data from a number of large insurance companies in the Netherlands. The database covers water related damage to private buildings (data available from 1986 until 2010) and building content (data available from 1992 until 2010). Insurance is provided only in the case of extreme rainfall and the threshold for the rainfall to be considered as extreme is set by the Association.

2.7 Review of current approaches in flood damage assessment

This paragraph provides a review of the flood damage models developed up until now. This paragraph aims at learning about the concepts used in damage modelling through literature review. Another aim is finding the vulnerable spots and uncertainty sources of the reviewed models. The choice of models for the review has been based mainly on the information availability (method descriptions in scientific papers and in reports in English). The macro scale models have not been reviewed since these are outside the scope of this study.

The reviewed flood assessment methods differ in various details, but they all follow the same concept using four information components supporting the damage estimate:

(1) hydrological characteristics, mainly corresponding to flood depth,
(2) elements at risk, often estimated using land use information or information regarding individual buildings, aggregating or disaggregating information,
(3) value of elements at risk,
(4) susceptibility of the elements at risk to the hydrological characteristics, mostly defined using depth–damage curves.

Table 2.4 provides a list of choices for the model development.

Table 2.4 List of choices for a damage assessment model development

Purpose	Damage categories	Flood damage	Spatial scale	Model development	Damage function	Impact & resistance parameters
Coastal floods Fluvial floods Pluvial floods High ground water Combination	Residential buildings Non-residential (commercial, public) buildings Infrastructure Agriculture Traffic disruption People	Direct Indirect Tangible Intangible	Macro Meso Micro	Empirical Synthetic Combination	Relative Absolute	Inundation depth Area Flow velocity Duration of inundation Building use/business sector Building type, material

After the review, the model similarities and differences can be listed as follows:

All models that can assess damage to more than one economic sector (not only private households, but also industry, infrastructure and agriculture) are synthetically and synthetically/empirically developed models (HAZUS-MH, MCM, CM and SM). All empirically developed models assess damage only to private households.

- Three empirical models are developed for private household damage assessment only (FLEMOps, method by Schwarz & Maiwald and method by Dewals). One model is developed specifically for commercial building damage assessment (FLEMOcs).
- The highest resolution for the damage assessment is provided by the method developed by Dewals, 2 x 2 m, and FLEMO models follow with 25 x 25 m grids.
- Three methods use only one impact parameter – water depth (method by Dewals, HAZUS-MH and method by Schwarz & Maiwald), all other methods use at least one more parameter – flood duration (SM and MCM), water velocity (CM at local scale and SM) and precaution measures together with contamination (both FLEMO models).
- The only model that uses absolute functions is MCM.
- All models are developed to assess fluvial or coastal flood damage.

Table 2.5 provides an overview of the modelling approaches within Europe and the USA with a short description regarding their spatial scale, purpose (fluvial, pluvial, coastal flooding), economic sectors, data sources and the calculation outcomes. A more detailed description of the models can be found in Appendix A.

After the review, the model similarities and differences can be listed as follows:

- All models that can assess damage to more than one economic sector (not only private households, but also industry, infrastructure and agriculture) are synthetically and synthetically/empirically developed models (HAZUS-MH, MCM, CM and SM). All empirically developed models assess damage only to private households.
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- The highest resolution for the damage assessment is provided by the method developed by Dewals, 2 x 2 m, and FLEMO models follow with 25 x 25 m grids.
- Three methods use only one impact parameter – water depth (method by Dewals, HAZUS-MH and method by Schwarz & Maiwald), all other methods use at least one more parameter – flood duration (SM and MCM), water velocity (CM at local scale and SM) and precaution measures together with contamination (both FLEMO models).
- The only model that uses absolute functions is MCM.
- All models are developed to assess fluvial or coastal flood damage.

Table 2.5 Overview of reviewed damage modelling approaches in Europe and USA

Synthetic development models		
Name, country	*Purpose, economic sectors*	*Short description*
Czech Methods (CM), Czech Republic	Fluvial floods. Residential, industrial, agricultural, infrastructure	Relative functions used to calculate direct tangible, indirect and intangible damage for local, regional and national size areas. For the local scale use 200 building sub-types are distinguished, each having a synthetical damage function adjusted by actual damage data.
Multi-Coloured Manual (MCM), UK	Coastal and fluvial floods. Residential, non-residential properties, industry	Around 120 abs. damage functions are used to calculate direct tangible/intangible damage for residential properties and for m^2 per property of non-residential properties Flood duration is taken into account. Software tool ESTDAM. Used for all spatial scales.
Synthetic/empirical development models		
Standard Method (SM), The Netherlands	Coastal and fluvial floods. Residential, industrial properties, infrastructure, agriculture	11 relative depth-damage functions available for different asset categories are used to calculate direct and indirect damage for 100x100 m grid cells. Approximate total asset values are obtained from official statistics. Additional impact parameters are flow velocity and flood duration. Software tool HIS-SSM.
HAZUS-MH, USA	Coastal and fluvial floods. Residential, non-residential properties, industry, agriculture, infrastructure	Relative functions used to estimate area-weighted damage as a percent of replacement costs at a census block (for the calculation, a uniform building distribution is assumed for a census block).
Empirical development models		
Method by Dewals and Ernst, (2008) Belgium	Fluvial floods. Residential and non-residential properties	Relative depth-damage functions that have been developed by German FLEMO are used to assess direct tangible damage to buildings performed on a 2x2 m analysis grid.
FLEMOps, Germany	Fluvial floods. Residential properties	Relative functions used for micro scale (building-by-building) and meso scale (land-use units) direct tangible damage assessments. Damage calculated per building or a grid cell. Building type and quality, water level, contamination and precaution measures used as input and resistance parameters.
FLEMOcs, Germany	Fluvial floods. Commercial buildings, inventory, equipment, stock	Relative functions are used to derive asset values per m^2 for every flooded grid (25x25 m) cell for 4 sectors and 3 company size classes. The average water depth per grid cell was used to assign the loss ratios via the loss functions to the asset values.
Damage and loss prediction model, Germany	Fluvial floods. Residential properties	Method focuses on considering the structural damage due to flood impact by defining five vulnerability classes. Repeatedly observed effects on buildings are used as indicators for the damage grade definition. The defined damage grades are used for unified damage evaluation. For the loss prediction, specific damage functions (SDF) are under preparation. Functions refer to the building type (or flood vulnerability class) or to the structural damage grade.

Sources: Egorova et al. (2008), Satrapa (2006), Dewals et al. (2008), Scawthorn et al. (2006), Ding et al. (2008), Thieken et al. (2005, 2008), Kreibich et al. (2010), Seifert et al. (2010), Schwarz & Maiwald (2008), Merz et al. (2010), Messner et al. (2007), Meyer & Messner (2005)

3 Uncertainty sources in flood damage assessment modelling

This chapter aims to answer the second and third research questions regarding the uncertainty sources found in the damage assessment models developed up until now. This chapter is divided in two parts. The first part illustrates the uncertainties focusing on model characteristics important for this study. The second part describes the uncertainty analyses performed by several authors and aims at finding the knowledge gaps in uncertainty assessments.

3.1 Uncertainties in the current flood damage assessment methods

It is important to distinguish two basic uncertainty categories which are fundamentally different from each other: natural and epistemic uncertainty. Epistemic uncertainty can be decreased by an increase in knowledge, while natural uncertainty is inherent to the system and cannot be reduced by more detailed information (Ferson & Ginzberg, 1996, quoted in Apel et al., 2004). Damage assessments are based on assumptions and decisions about models, their parameters and input data. In many cases different options are available and then it is the analysts' choice, which model, which parameters to use. Consequently, uncertainty spreads through the model calculations and gathers in the final damage estimate (Merz & Thieken, 2005).

Natural uncertainty has the following properties (Apel et al., 2004; Merz & Thieken, 2005):

- it refers to quantities that are inherently variable over time, space, or populations of individuals or objects,
- it is a property of a system,
- it is not reducible.

Epistemic uncertainty is characterised as follows:

- it is related to the analyst's ability to understand, measure, and describe the system under study,
- it is regarded as a property of analyst,
- it considers incomplete knowledge, inability to measure all variables,
- it can be reduced.

After having reviewed the flood damage assessment models, a list of uncertainties becomes evident. These uncertainties can be divided into previously mentioned uncertainty categories and these are discussed in the following paragraphs. Both natural and epistemic uncertainties can be further divided into model uncertainty and input data uncertainty. The uncertainty sources are presented in Table 3.1.

Table 3.1 Uncertainty sources in the damage assessment models

	Model uncertainty	*Input data uncertainty*
Natural	Choice of assessment model selection	Total asset value per object Asset value change in time (lack of updates for absolute depth-damage curves) Water level at which the maximum damage for an object is reached Variability of damage influencing factors in time and space Variability of potential damage between similar elements at risk Unpredictable future development (land use changes, socio-economic development, climate change impacts)
Epistemic	Choice of depth-damage functions Use of more than one damage influencing factor Model transferability (use for another time span and application for different areas)	Depth-damage functions Object/building and content value estimation Land-use/building type Uncertainty in damage influencing factors Other model generated input data (e.g. hydrodynamic model)

3.1.1 Input data uncertainty

The uncertainty in the damage functions originates from the great natural variability of observed damage between similar elements at risk. For example, two private houses of the same building type located next to each other can experience differences in damage during the same flood event. One of the reasons is residents' capability to perform damage reduction measures (e.g. move moveable items to dry places). Moreover, the finishes of a building can be different based on the residents' personal taste; while one building can have a carpet as the flooring, other building might have tiles. These influences are not really predictable. The variability and vulnerability of the elements at risk can change over the course of time. For instance, technological changes can lead to increased susceptibility. In addition, future development can be unpredictable – there are the impacts of climate change, economic development and land use changes. Consequently, damage assessments for ex-ante events may not hold true after several years (Merz et al., 2010). Some models (Standard Method (Egorova et al., 2008), HAZUS-MH (Scawthorn et al., 2006)) use low resolution land-use maps with a limited number of land-uses classes that generalise the existing situation in the study area.

It is recommended developing depth-damage functions that represent local conditions and the building types present in the study area. For loss estimations in large areas, building oriented loss functions are often not feasible and are less reliable. Absolute depth-damage function data on property values must be regularly updated (Meyer & Messner, 2005).

Next, apart from inundation depth, other damage influencing factors (e.g. duration of inundation, flow velocity) are not generally considered, even though they are regarded as important. The main reasons as stated in Merz et al. (2010), is that the inclusion of other parameters would complicate the calculations and contribute to the uncertainty. Furthermore, these factors vary in time and space, they are difficult to predict and there is limited information on their effects on the objects they face. Moreover, every parameter included in the modelling is a source of uncertainty. An opposite view is expressed by Middelmann-Fernandes (2010), who considers additional factor incorporation important. The author proposes floodwater velocity inclusion in the damage calculations, creating velocity-depth-damage curves. Based on authors' research by applying both curve types (depth-damage and velocity-depth-damage), he concludes that both curves have their limitations. While depth-damage curves do not consider the fact that a building might fail (by moving off its foundations), therefore underestimating the damage, velocity-depth-damage curves identify only those buildings that do fail again underestimating the damage. Middelmann-Fernandes suggests using both curves as it would potentially provide more accurate total direct damage to buildings.

The uncertainty concerning the damage estimate of the respective study should be documented as the level of measurement uncertainty in the results should be known by the interested party. A very approximate damage estimate can be sufficient for a strategy decision, but insufficient if specific protection measures have to be implemented. One of the approaches to uncertainty documentation includes pointing out the minimum and maximum building asset values when they are assessed by an expert. In this way a range is formed which shows where the real value most likely stands (Messner et al., 2007).

3.1.2 Model uncertainty

Model uncertainty can be described with the question: "which model to use for the damage assessment?" The study by Merz et al. (2010) and the report by Messner et al. (2007) show that there are many different damage models available for every study area scale and for different purposes (damage calculation to residential buildings, industry, agriculture etc.). Several studies (Apel et al., 2009, Merz et al., 2009, Bubeck et al., 2011) use not only one damage model, but several, in order to compare the outcomes and to eliminate those models that perform outside a set confidence level. Using different models also means using different depth-damage curves and functions. Some models take into account not only one impact parameter, which is typically water level, but additional parameters, for example FLEMOps also uses scaling factors to consider contamination and precaution measures (Thieken et al., 2008) enabling the possibility to assess the damage with greater accuracy. Consequently, if a damage assessment is done using only one model, the results cannot be completely certain.

Selection of a hydrological model is important for pluvial flooding. The building damage is calculated based on the information if it is firstly flooded at all and secondly, to what extent. If the hydrological model does not perform well (has an uncertainty in resulting flood heights), the results cannot be fully reliable.

3.2 Uncertainties addressed in literature

Uncertainties can be addressed in numerous ways, for instance by using scenarios to create a range of possible outcomes. Various studies look at uncertainty in a range of components that are included in a damage assessment. Some studies look at uncertainties in a specific component, for example the direct damage calculation part of the assessment (Merz et al., 2004; Egorova et al., 2008) or the influence on flow velocity on the damage (Kreibich et al., 2009). More recently studies have focused on the combined uncertainty in various components of flood damage assessments. Merz & Thieken (2009), for instance, used different flood frequency curves, inundation models and damage models to estimate uncertainty bounds around flood risk curves. A similar approach was used by De Moel & Aerts (2011) who explored uncertainties in damage models, inundation depth and land use. Apel et al. (2004, 2008) has quantified the contributions of different uncertainty sources demonstrating, where the largest uncertainty reduction can be gained by improving the process understanding or modelling techniques. Apel et al. (2009) recommend a combination of hazard and flood loss model that represent the best compromise between the accuracy of results and the modelling effort. Table 3.2 shows a list of short method descriptions for the uncertainty assessment as well as the main findings from the reviewed studies.

Table 3.2 Uncertainty assessment methods and study conclusions

Author	*Method*	*Main conclusions*
Merz et al. (2004)	Uncertainty analysis regarding flood damage estimates to buildings at municipality level. Approximately 4000 damage records are analysed using HOWAS dataset (the original dataset containing information from 9 floods in Germany from 1978 – 1994).	The damage estimate uncertainty decreases with increasing number of flooded buildings in the study are. Flood damage of a single building of the use "private housing", with a probability of 95% the true but unknown damage was between 700 and 212000 DM[9]. For a study area, there is a min number of buildings to be assessed in order for the damage value to be true but unknown with a 95% probability. Uncertainty in the estimate for an industrial area is much greater than for a residential area when the same number of buildings is affected by flood.
Merz & Thieken (2009)	Six different models (3 depth-damage functions and 3 options of the empirical model FLEMOps, all meso scale) used to assess direct financial damage to residential buildings due to river flooding. Validation source: floods caused by long duration rainfall (10-20 days) in 1993 and 1995 in city Cologne. Natural and epistemic uncertainty assessed separately. Concept of parallel models used, the outcome is an uncertainty band that represents the incomplete knowledge.	Contribution of three modules involved in damage assessment has different shares in the uncertainty. At a return period T=10, damage estimation module has the lowest share, inundation estimation has the highest share, while the flood frequency estimation is in between. Damage estimation module has the lowest share also for other considered return periods (T=100, T=1000).
Apel et al. (2004, 2008)	Dynamic-probabilistic modelling system for the calculation of flood risks is used, which enables a cumulated flood risk assessment of a complete river reach considering dike failures at all dike locations. The model uses simple, but computationally efficient modules to simulate the complete flooding process chain. The flood damage estimation is performed for residential buildings using a stage-damage function. Predictive uncertainties are estimated: data, parameter and model uncertainty.	The predictive uncertainty considering all sources is comparatively high, with rising uncertainty for extreme events. The more it is extrapolated beyond the length of the data series to extreme events, the higher the uncertainty of the predictions gets. The combination of single uncertainty sources showed that they are not strictly additive, but compensate each other to some extent. This implies that a reduction of one of the major uncertainty sources does not necessarily reduce the total predictive uncertainty. All major uncertainty sources have to be reduced for a reduction of the overall predictive uncertainty.
Apel et al. (2009)	Search for the best combination between 3 models that calculate water level (linear interpolation, 1D/2D and 2D) and 3 damage assessment models (meso scale DDF, FLEMOps for micro and meso scale) for direct loss estimation for residential buildings. Outcomes compared between models and with flood loss data from floods in 2002 in Germany (water levels from watermarks at 380 buildings, total loss from SAB[10]).	Selection of the flood loss model has a much larger impact on the final risk estimate than the hydr. model. Reasonable estimates can be achieved for the wrong reasons – errors caused by hydr. model could be compensated by errors in damage model, thus both components have to be evaluated separately. All hydraulic models were able to simulate the max water levels of the flood within certain accuracy lev-els.
Kreibich et al. (2009)	Investigation of the influence of flow velocity, water depth and combination of these impact parameters on various flood damage types in five communities affected by the Elbe catchment flood in Germany in 2002. 2-D hydraulic models with high to medium spatial resolutions used to calculate the impact parameters at the sites in which damage occurred.	A strong influence of flow velocity on flood damage was only identified for structural damage of road infrastructure. The total energy (according to Bernoulli eq.) is sug-gested as a suitable flood impact parameter for reli-able forecasting of structural damage to residential buildings above a critical impact level of 2m of en-ergy head or water depth. However, further research is necessary to verify these results.

[9] Deutsche Mark, the former official currency of Germany
[10] Saxonian Relief Bank

Table 3.2 Continued

Bubeck et al. (2011)	The study investigates whether variations in absolute and relative damage estimates between two different damage models (RAM and DSM) result from differences in damage functions or from the estimation of the exposed asset values. The variations due to the application of different flood damage modelling approaches are compared with the uncertainties originating from land-use projections.	Different methods assume different water levels at which the maximum damage is reached for the developed depth-damage functions. The max damage for similar damage categories differ significantly between the two models the study compares. RAM[11] for the residential category calculates a max damage of 288 €/m^2, while DSM[12] calculates 910 €/m^2 for high density urban areas and 400 €/m^2 for low density urban areas. The results show that both model outcomes differ significantly in terms of absolute damage estimates by a factor ranging from 3.5 to 3.8. Estimating relative flood damage, both modelling approaches provide similar results (differing by a factor of 1.4). Authors show that differences in the maximum damage values have a slightly smaller influence on variations between the two models (factor 1.8) than differences in the damage functions (factor 1.93-2.13).
De Moel & Aerts (2011)	Uncertainty related to the four information sources (inundation depth, land use, value of elements at risk and depth–damage curves) is assessed by manually varying the components in a "one factor at a time" approach. Different land-use maps are used to illustrate uncertainty related to the estimation of elements at risk and different damage models are used to estimate uncertainty related to the value and susceptibility of elements at risk. Inundation depth is varied manually in order to assess the sensitivity of the damage estimate to this component. Case study area: a dike ring on the South bank of the river Meuse.	Variation in absolute flood damage estimates using different land use maps is relatively small. The choice and quality of the damage model components have a larger influence on the damage estimate than the uncertainty in the hydrological component. The results indicate that, assuming the uncertainty in inundation depth is 25 cm (about 15% of the mean inundation depth), the total range of outcomes can vary up to a factor 5–6.
De Moel et al. (2012)	A breach growth model, an inundation model and a damage model are subjected to a Monte Carlo analysis in order to determine the sensitivity of the model chain to different assumptions in the input parameters of these models, and to assess the uncertainty surrounding the resulting damage estimates for a coastal storm surge flooding for a study area characterized by low-lying polder areas, partly below mean sea level).	Considerable uncertainty is associated with the flood damage estimates related to coastal storm surges. The upper and lower estimates of the 95% confidence range are easily four times smaller or larger than the median. The most influential parameter contributing to this uncertainty found in this study was uncertainty in the shape of depth-damage curves. The contribution of uncertainty in parameters related to the damage calculation is about equal to the contribution of parameters related to the volume of the inflowing water after a dike breach.
Freni et al. (2010)	One simple and one detailed urban drainage model to show if using a detailed model contributes to the reduction of uncertainty in the damage estimate for an urban flooding.	The uncertainty bands in depth-damage curves are in the range of 40%–50% of the average value, depending on the analysed water depths. The use of detailed modelling approaches (regarding the urban drainage model) has to be weighted accurately with the uncertainty provided by data availability, the advantages provided by detailed models may be largely absorbed by the uncertainty in damage estimation; thus, the additional computational costs of such approach may not be justified.

[11] The Rhine Atlas damage model
[12] The Damage scanner model

3.2.1 Damage model validation

Model validation is necessary for model evaluation – one has to know, if a model performs well in observed situations and whether it can be used for reliable predictions in unobserved situations. Unfortunately, model validation is rarely performed, which is why a qualitative damage assessment is hard to achieve. The reason for this drawback is the limited or non-existent data on real flood observations. Model validation is also necessary to evaluate the systematic estimation error presence (Merz et al., 2010).

Seifert et al. (2010) has performed validation of FLEMOcs model (damage estimation for commercial sector, developed by (Kreibich et al., 2010)) for both micro and meso scales. For the model validation at the micro scale, a leave-one-out cross-validation procedure was applied based on empirical data from three recent floods in 2002, 2005 and 2006 in Germany. One after another, each data point was singled out, and then the FLEMOcs model functions were derived on the basis of the remaining data. Finally, the loss ratios of the singled out data point were estimated using the FLEMOcs model developed without the particular data point. The errors of the model estimates were evaluated by their mean bias error, mean absolute error and root mean square error. The validation results reported by the authors show that the estimates of the building loss ratios are most accurate in comparison with the estimates of the loss ratios of equipment and goods, products and stock. The results show no bias and the mean absolute errors between 23-31%.

For model evaluation at the meso-scale, FLEMOcs has been compared with three relative meso-scale models that use loss functions and are commonly applied in Germany: MURL, ICPR and Hydrotec[13]. FLEMOcs and the three other models were applied to calculate flood losses in 19 municipalities in Saxony, Germany. The calculation results were compared with each other and also with official loss records on the municipality level. The model comparison with official loss records and with other models showed that in municipalities with minor losses, all models overestimate the losses. FLEMOcs provides good results in large areas with many affected companies and high expected losses.

The FLEMOps damage assessment model developed by Thieken et al. (2008) has also been validated by comparing the model outcomes with the same three different damage models as used for meso-scale FLEMOcs validation (MURL, ICPR and Hydrotec). Results were compared with the 2002 flood event in Germany. While MURL and ICPR underestimated the values and Hydrotec overestimated, FLEMOps outcomes were the best for a half of the affected municipalities and for the rest it overestimated the calculation results.

Dewals et al. (2008) has validated the economic damage assessment model developed in Belgium. The computed damage values were compared with reference values collected by the Belgian Disaster Fund after real flood events. The validation showed that computed damage values were overestimated. Authors state that the reason was the lack of information in the reference data collected by the Disaster Fund and not the model performance itself.

The most commonly used approach by comparing observed and simulated data is only partially applicable, since the damage assessment contains statements about events that have not been observed before. Potential uncertainty source analysis is one alternative way to validate a model. It is necessary to search for the assumptions that dominate in the result, so that the sensitive aspects of the damage modelling can be identified. If the decisive elements of the damage modelling are reliable, then it is expected that the resulting damage estimate will be reliable as

[13] MURL and Rhine-Atlas (ICPR) are meso and macro damage assessment models used in all economic sectors for damage estimation along the river Rhine, these methods distinguish mobile and immobile assets. Relative damage functions for MURL and Hydrotec have been derived from the HOWAS database. Damage functions for ICPR are synthetic and extended with empiric data (Merz et al., 2010).

well. If decisive elements have considerable uncertainty, then the damage estimate should be put forward with caution (Apel et al., 2008; Merz et al., 2010).

3.2.2 Knowledge gaps regarding pluvial flood damage modelling

After the review of the uncertainty assessments in the literature, the main knowledge and research gaps are found to be as follows:

1. A clear description is missing of possible pluvial flood water depths for both flat and sloped urban areas (what is an average pluvial flood water level?).
2. There are no depth-damage curves or functions developed particularly for pluvial floods.
3. There is no uncertainty source quantification and evaluation for flood damage assessment models regarding pluvial floods.
4. There is no damage assessment model validation for events with water depths common for pluvial floods (assumed to be < 1 m).
5. Depth-damage curves and functions developed for fluvial and coastal floods have not been tested and applied for pluvial flood assessment.

Third point regarding the uncertainty source quantification and evaluation for pluvial flooding will be addressed in Chapters 4 and 5.

4 Materials and Methods

This chapter describes the relevant materials and methods regarding this study. In the following chapters the description is provided regarding pluvial flooding context and the synthetic damage calculation procedure with the damage assessment model HOWAD-PPEVENT. Furthermore, this chapter provides the case study description. Also, the fourth research question regarding the uncertainty sources in HOWAD-PREVENT damage assessment model is answered in this chapter.

4.1 Pluvial flooding context

Urban flooding occurs having characteristics that differ from characteristics usually considered in fluvial and coastal flood risk analysis in terms of dimensions (size of the inundated area, inundation depth) and quantities (damage amount, monetary loss). In general, the models developed up until now are not designed explicitly for pluvial flood damage assessment. Damage model developers have been focusing on coastal and fluvial floods, because these have caused the greatest flooding events in the last decade in terms of costs and the number of casualties. Some reported examples are floods in Germany in 2002 (rivers Elbe, Danube and their tributaries) reported by Kreibich et al., (2005), and Thieken et al., (2005, 2007) and floods in UK in 2000 and 2007 reported by Dawson et al., (2008). Urban flooding can receive less attention than other floods due to the smaller scale of individual events.

Van Riel (2011) in his MSc study has illustrated the potential pluvial flood impacts in an urban area, these are presented in Table 4.1.

Table 4.1 Potential pluvial flood impacts (adapted from van Riel, 2011)

Material	Residential, commercial buildings, content	Public buildings and content	Infrastructure	Public space	Public utilities and networks
Economic	Electricity disruption	Communication network disruption	Traffic disruption	Business turnover loss	
Emergency assistance	Fire department services	Police department services	Sewer system management services		
Health	Health impacts due to contact with floodwater		Health impacts due to damp house and associated fungi		
Discomfort	Inhabitants' experience of all relevant impacts in a flood event				

As already stated in the introduction, coastal and fluvial floods cause damage which in monetary terms can be measured in millions of Euros, while pluvial floods is only a small fraction of this amount. As stated by ten Veldhuis (2010), assuming a flood depth of 10 cm, the material damage to flooded residential buildings range from 1,000 to 30,000 Euro per flooded building, and for commercial buildings damage ranges from 2,000 to 30,000 Euro, although the cumulative material damage could be significant due to the relatively high occurrence frequency (Freni et al., 2010; ten Veldhuis, 2010). In addition, water depths considered in fluvial and coastal flooding vary from 0,5 to several meters, while for pluvial flooding water depth is in the order of tens of centimetres in flat areas (ten Veldhuis, 2010). Douglas et al. (2010) describes pluvial flooding events in 2004 and 2006 in Heywood, UK. While in the majority of affected houses the water levels rose up to 0,3 m, only in one case the water in the house exceeded 1 m. The entry of floodwater into buildings was generally via the airbricks or doors.

The scope of this study is limited to residential buildings only. For a building, the most crucial water entry points are located at the height of 0,3 m – ventilation gaps in the building wall, possibly leaking small basement windows, unsealed doors and large windows. The presence of absence of a doorstep and its height is of utmost importance when it comes to the possibility of water to enter the building.

4.2 Overview of the model

4.2.1 Model setup

The HOWAD-PREVENT model has been developed in Leibniz Institute of Ecological Urban and Regional Development (IOER) in Dresden, Germany. The model calculates direct tangible flood damages from local to regional scale focusing on residential and non-residential buildings as well as their contents. The model structure follows Source (flood generated by heavy rainfall, storm surges) – Pathway (ground surface) – Receptor (buildings) – Consequence (potential damage) concept. It involves a classification of buildings in a study area by building type and uses synthetic depth-damage curves to calculate the damage caused by both high groundwater levels and flooding (Neubert et al., (forthcoming)).

The damage modelling consists of five main work steps:

(1) Building type identification and systematization in the study area;
(2) Analysis of characteristic damage types that occur to the building type representatives;
(3) Technically correct refurbishment technique identification including the cost parameters;
(4) Building type specific synthetic depth-damage curve derivation;
(5) Respective component integration into the HOWAD-PREVENT model: water level, building data set, depth-damage curves.

The first step is the building analysis in the study area. Building types represent a number of buildings with similar features, such as size, the number of families housed, construction mode, materials and other details. The building type identification is based on geo-information analysis (maps, GIS layers available at several institutions with building polygons) and field surveys. This step results in a building type matrix, which provides a starting point for the creation of representatives. Then, representative buildings are documented and include drawings, floor plans, building functions and use, construction details and building condition. These representatives are used in the third step of HOWAD-P modelling approach. The level of building type subdivision considerably depends on the specific research question, selected spatial scale and resources. The highest possible resolution for damage calculation would need a house by house investigation on-site, which requires great effort and can be reasonably done for small urban areas.

The second step is recognition of relevant damage types to the building stock that can occur due to flooding. Depending on the type, intensity and extent of the damage, the required repair techniques can be defined. HOWAD-P model takes into account water and moisture damage.

The third step is combining previously defined inundation levels with the representative buildings. Each inundation level might cause different damage (recognized in the second step), thus each level defines the repair areas. Next, based on the information of required repairs for each inundation level, the refurbishment costs are calculated. The costs for each specific repair are found either from technical literature on refurbishment or using expert interviews regarding building restoration, technical drying etc.

The fourth step is visualisation of the relation between a defined inundation level and the allocated refurbishment costs – depth-damage curve creation, which are building type specific. The calculated values in the third step are the fixed points of the depth-damage curves. Values between the fixed points on the curve are derived by linear interpolation. Validation of these synthetic depth-damage curves can be accomplished looking at detailed cost determinations of technically correct repairs after a real flood event, but this step is still in progress (Neubert et al., (forthcoming)).

The last step is the damage calculation. Damage is calculated on the level of individual buildings applying the building type specific depth-damage curve. A HOWAD-P toolbox is added to ArcMap software. The model realises the following steps: (1) exposure determination – combination of water levels (acquired from hydrodynamic modelling) with all buildings present in the study area, (2) depth-damage function combination with the resultant water levels at each building, (3) damage calculation for every object and (4) results. Figure 4.1 presents the model structure graphically.

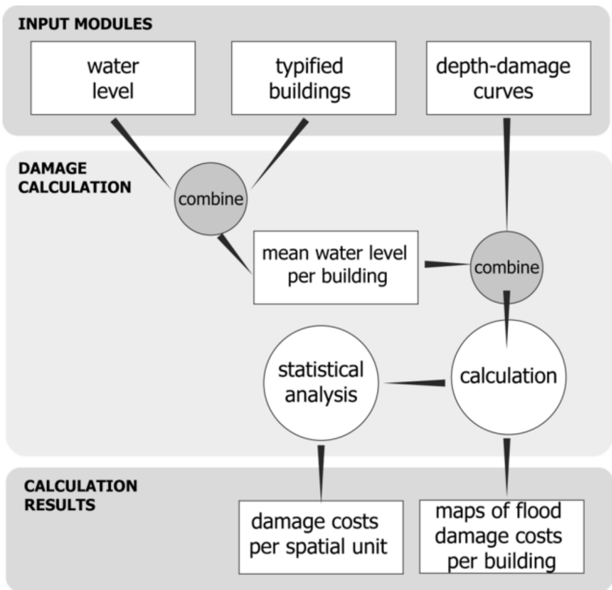

Figure 4.1 HOWAD-PREVENT damage calculation structure (adapted from Neubert et al. (forthcoming))

The model has been applied by its developers for regional case studies:

(1) study regarding groundwater inundation, where the size of the study area reached 100 km^2 with 23000 buildings, in Dresden, Germany,
(2) study regarding fluvial floods in Dresden-Kleinzschatchwitz, Germany, with the study area of 1,5 km^2 and 1300 buildings,
(3) study regarding pluvial floods in Heywood, UK, with the study area of 0,4 km^2,
(4) study regarding fluvial floods in Valencia, Spain, with the study area of 0,4 km^2 and around 550 buildings.

Unfortunately, the amount of time required to complete these studies has not been indicated.

4.2.2 Evaluation of the model concept, uncertainties and their influence on model outcomes

Overall method

The main difference from other damage assessment models is the highly detailed approach when the elements at risk are considered. This detailed approach aims to reduce the epistemic uncertainty, if performed with great accuracy. The downside of this very detailed approach is the great amount of time and resources required, that are increasing with an increasing size of the study area and the number of buildings. HOWAD-P considers buildings and their inventory. The building classification has to be done building by building using the available resources (available maps, field surveys). Based on the required level of detail, also the depth-damage curves can be created to represent a significant building attribute, for example the presence or absence of a cellar. Another detail is the possibility to indicate if a building has any flood precaution measures. In all other aspects, the overall method is similar to most other damage assessment methods:

- Depth-damage curves are used for the damage assessment,
- Water depth is used as the flood impact parameter,
- Assessment is done only for direct tangible damage.

Input data

(1) *Water level*. The water level has to be obtained from hydrodynamic modelling, if the damage is assessed for certain flood scenarios (today's situation, expected future developments combined with several occurrence probabilities etc.). The water level should be available with high spatial resolution (2x2 m), so it is possible to assign at least one water depth value to each building polygon. The model recognizes positive water level values for flooding and negative values for groundwater inundation. For this aspect the model developers have not considered a possibility that a city might be located below the mean sea level and that it can have negative values as the ground levels, as it is in Rotterdam and the study area. The whole area had to be "lifted" in order to have positive values for the ground and water levels. The water level values are one source of the epistemic uncertainty. The model calculates an average water depth value for each building polygon taking into account every grid cell that touches the polygon and that is located under it.

(2) *Building types*. The model developers are aiming at a very detailed building classification. Consequently, access is required to different information sources: several types of maps (building polygons, building use, building construction year etc.), access to building plans for construction details (building plan, cross-section, floor area, number of floors, floor and wall construction materials, presence of cellar), access to buildings themselves for a field survey, access to specific repair cost information and contact with specialist engineers. Information regarding building types is subject to epistemic uncertainty (it depends on data updating frequency), as buildings might have repairs, refurbishment (e.g. change of floor material) which will alter their susceptibility to flood as well as change the amount of money necessary for repairs.

(3) *Depth-damage curves.* Absolute DDC creation for the study area was outside the scope of this project. But analysing the examples of curves in Neubert et al. (forthcoming) and in SMARTeST deliverable D4.1, the damage values per m^2 for several building types (detached, semi-detached houses and multi-family houses) are in the range of 250-800 eur if looking at the water level range of 0 – 1 m. What is interesting to point out, is that some of the curves give building damage even if the water level is 0 m. If the depth-damage

curves would have been relative instead of absolute, it would be possible to apply them in a wider range of different locations (not only within Germany and neighbouring countries), since the costs are not equal within different countries. Depth-damage curves are subject to both epistemic and natural uncertainty. The reduction of epistemic uncertainty is possible if great effort is put into the creation of these curves. At the same time it is not possible to look in every building and to create a damage curve for each individual case, so the variability of potential damage between elements at risk plays a role in adding uncertainty.

Modelling

For this study, a HOWAD-PREVENT demo version was available, which could calculate damage for 100 building polygons and for 4 building types which increased the modelling time, since the study area had to be divided into several separate files. The modelling using HOWAD-PREVENT toolbox in ArcMap software is straightforward. After the relevant datasets have been created, the model runs and provides the calculation results. Nevertheless, the user has to be careful and provide the files in correct formats. If an error is generated, it is not possible to find out, which input source or other component (e.g. software itself) generates the error, since the toolbox is password protected. The relevant datasets necessary for modelling are listed below:

(1) Water level dataset (GRID)
(2) Building dataset (polygon shape file .shp)
(3) Precaution measure area selection (polygon shape file, if applied)
(4) Depth damage functions for each building type (table in Excel .xlsx)

4.3 Study area description – Pendrecht

4.3.1 Basic features

The area for the case study in Rotterdam has been selected based on three criteria, also taking into account the limited time for modelling within the MSc project: (1) the area had to be as homogeneous as possible (the predominant building type had to be residential buildings), (2) the area had to have less than 1000 building polygons and (3) there had been some events related to rainfall (water on a street, water in basement, water in house) reported by the citizens. During the search for an appropriate location, no information was found of a certain pluvial flood event (internet, newspaper headlines, and personal communication with the Municipality of Rotterdam[14]). Finally, the location was selected based on the homogeneity of the area.

Pendrecht is situated in the South of Rotterdam, the size of the investigation area (see Figure 4.2) is around 0,28 km^2 (approx. 1/3 of the neighbourhood) with 630 building polygons. The area is located below the mean sea level (-2 – 0 m). Based on the information provided by the Municipality of Rotterdam, The Department for Urban Planning and Housing, this area has been developed starting in 1990s, and the latest buildings have been erected as recent as in 2010. The predominant building types are low and tall terraced houses as well as multi-family in row standing buildings.

[14] Some events found in Vlaardingen in December 2011/January2012, but the cause of the floods was not clear.

Figure 4.2 Study area location in Rotterdam
(Rotterdam GIS web, http://www.gis.rotterdam.nl/gisweb2/default.aspx)

4.3.2 Building types

There are 4 different building types present in the study area:

(1) Low terraced houses (LTH) (see Figure 4.3 left);
(2) Tall terraced houses (TTH) (see Figure 4.3 right);
(3) Multi-family in row standing houses (open block) (MRO);
(4) Other (garages, shops, children day care, church etc.).

Every building in the study area has been assigned a specific sub-type. There are 10 sub-types present as shown in Figure 4.4. The sub-type characteristics can be found in detail in Appendix D.

Figure 4.3 Predominant building types in Pendrecht: low and tall terraced houses (left), multi-family in row standing buildings (right)

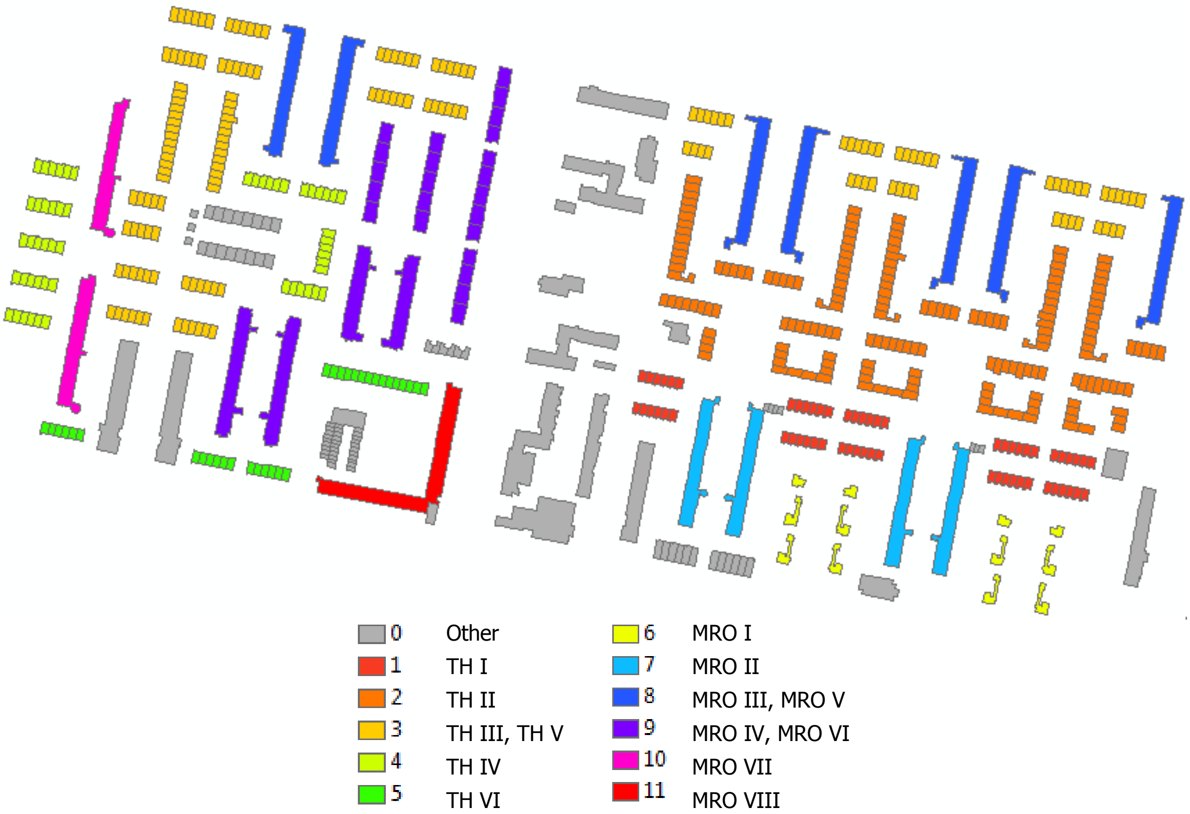

Figure 4.4 Building sub-types in the study area

As the height of the building and the number of storeys is negligible for pluvial flooding because of the low water levels (assumed to be < 1 m), tall terraced houses and low terraced houses have been aggregated to one type – terraced houses. Majority of the multi-family houses have been built as adapted building – the ground floor was not at the street level, but raised approx. 0,5 – 1,0 m above street level, so the entrance was also above the street level. On the other side, most of these buildings have a basement, so the basement and its contents might suffer in the case of a flood. Majority of the terraced houses have the entrance 0,1 – 0,15 m above the street level, so these buildings are subjected to inundation if there is significant water level on the street.

Table 4.2 shows the sources used for building type classification, their availability and reliability.

Table 4.2 Building type classification information sources

Map/Action	*Source*	*Application, availability*
Aerial maps	Google maps	Help in area selection, building classification. Most recent maps available for Rotterdam (2012)
Postal code areas	Municipality of Rotterdam	Boundaries for the study area
Building polygons	Municipality of Rotterdam, GBK: Large-scale basic data, *grootschalige basis kaart*	Building polygon shape file (Feb 2012)

Table 4.2 Continued

Map/Action	*Source*	*Application, availability*
Building function (zoning) plan	GIS Web Rotterdam, *Bestemmingsplannen*	Help in area selection, available with access to Rotterdam GIS Web (http://www.gis.rotterdam.nl/gisweb2/default.aspx)
Building types	Google maps, field survey, http://www.bouwkostenkompas.nl/	Building type categorization based on field survey, building types taken from *Bouwkostenkompas* and categories proposed in HOWAD
Construction year	Municipality of Rotterdam, Archive	Not readily available in a map as an attribute to building polygon. Partly available on old building construction maps, where every building has a code: yy-aaaa-bb (y for year), not 100% reliable
Blueprints (plans, cross-sections)	Municipality of Rotterdam, Archive	Only hard copies available. Not all of the required information present (the most absent – wall and floor materials and their thickness)
Ground area	Arc Map 10.0	Calculation in ArcMap
Basement	Field survey, blueprints	
Foundation type		Not available
Building floor, wall material and thickness	Not available	Not available, assumed using the most likely from www.paroc.com catalogue. Other sources: experienced architect, building engineer
Building height	*3D Stadsmodel > Rotterdam 3D (gebouwhoogten)*	Rotterdam 3D, for homogeneous area selection and DEM validation, additional information

4.3.3 Water level

Water levels have been obtained using Digital Elevation Model (DEM) for Rotterdam which has +/- 7 cm accuracy (Veldhuis C., Gementee Rotterdam, pers. com.). The DEM has been constructed from data acquired by the Light Detection And Ranging[15] (LIDAR) method. The resolution of the original DEM file was 0,5 x 0,5 m with filtered terrain layer – all the buildings, trees, cars have been extracted and in these areas the map has blank spaces without any information regarding the elevation. A Kriging method using ArcMap 10.0 (explained in detail in Appendix C) was applied in order to fill these voids with values. A study from Reuter et al. (2007) suggests this method to be used in flat areas. Four water level depth raster files were created by adding a certain water depth (0,3 m, 0,5 m, 0,6 m, and 0,7 m) to the deepest point in the study area which, based on the elevations, was presumed to be -1,80 m (canal banks) (see Figure 4.5).

The GIS processing schemes can be found in Appendix C.

[15] LIDAR – optical remote sensing technology that can measure the distance to, or other properties of a target by illuminating the target with light, often using pulses from a laser (Wikipedia).

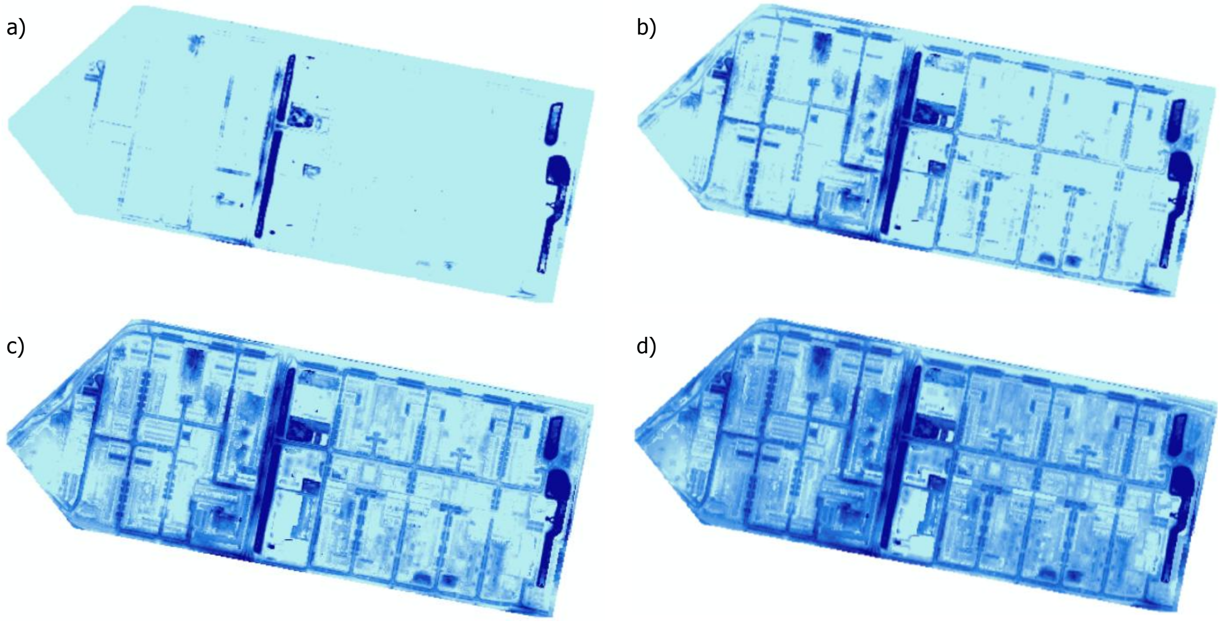

Figure 4.5 Four water level situations in the study area: a) +0,3 m, b) + 0,5 m, c) +0,6 m, d) +0,7 m

4.3.4 Depth-damage curves

Due to the limited time for the MSc study, it was decided to not to create new curves for this case study. Depth-damage curves for the modelling have been taken from the HOWAD-P report (SMARTeST D4.1) UK case that has been developed for a case study in Heywood. The curves in this project are created by taking only two relevant points (h=0 m and h=1 m) and the values in between have been linearly interpolated (see Figure 4.6). The inventory damage is not included in this calculation.

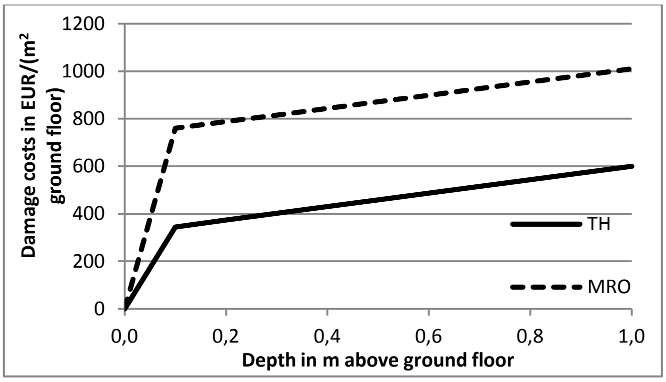

Figure 4.6 Depth-damage curves used in this study (adapted from a case study in Heywood)

4.4 Method

Sensitivity of the damage calculation to a certain component is presented as a factor, which is calculated by dividing the highest by the lowest damage estimate resulting from the variation in the component, keeping the other components equal. This factor shows how far off an estimate can be. The following method will be used for the model evaluation and sensitivity analysis:

the model performance will be assessed by testing three water level and two building type combinations:

1) All water levels will be combined with a shape file, which has two building types (484 TH and 85 MRO), and consequently uses two different depth-damage curves. The curves have two points containing real values, and the points in between have been linearly interpolated.
2) All water levels will be combined with a shape file, which has one building type (539 TH), and consequently uses one depth-damage curve.

5 Results

This chapter describes the modelling outcomes. Chapter 5.1. contains brief calculation results and Chapter 5.2. provides uncertainty quantification.

5.1 Modelling results

Following the method described in Chapter 4, the acquired modelling results are presented in Table 5.1. It has to be taken into account that the total damage presented in column No. 3 does not represent the real values for the case study area, since the selected depth-damage curves have not been created for this specific study area. Water level +0,3 m was discarded as it did not cause any flooding. Figure 5.1 shows the assigned water level for damage calculation for each building polygon indicating the flooded buildings for each water level scenario. All other results (damage per m^2 and total damage per building) in maps are presented in Appendix B.

Results show that there is significant increase in the number of flooded buildings and consequently the damage with a water level increase of each 0,1 m step meaning that the model estimates are sensitive to water level changes. As expected, there is difference in damage estimates, if two different depth-damage curves are used.

Table 5.1 Modelling results combining two building type and three water level combinations

Run No.	Number of building types	Water level [a)]	Total damage [b)] [Eur]	Number of flooded buildings [c)]
1	1	+ 0,5 m	1 517 310	17
2	1	+ 0,6 m	7 245 290	198
3	1	+ 0,7 m	17 764 435	511
4	2 [d)]	+ 0,5 m	3 147 430	17
5	2	+ 0,6 m	12 267 497	198
6	2	+ 0,7 m	27 847 908	511

a) The deepest ground level point in the study area + *x* m (*x* =0,5, 0,6 and 0,7).
b) Total calculated damage for all building polygons in the study area.
c) Out of 539 building polygons in total. Flooded – mean water level for the building polygon is 0,1 m and higher.
d) 484 building polygons of type TH, 85 building polygons of type MRO.

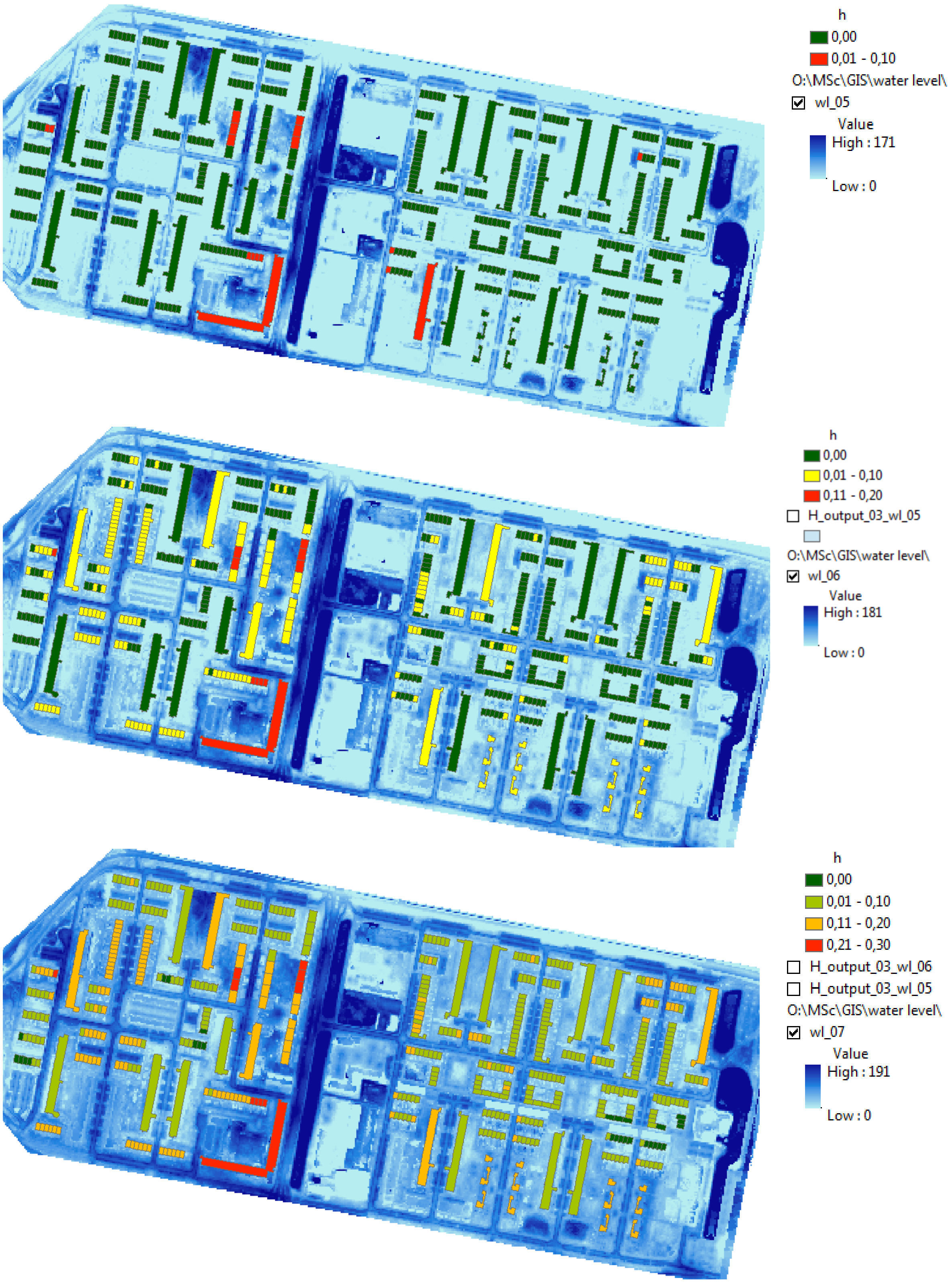

Figure 5.1 Assigned water levels for each building polygon [h in meters].
Top: +0,5 m (run no. 1), middle: +0,6 m (run no. 2), bottom: +0,7 m (run no. 3)

5.2 Model and input data uncertainty

All three input data sets (water level, building types and depth-damage curves) have been found to be a source of uncertainty each having a different order of magnitude. An additional uncertainty source is how the model calculates the mean water level per building polygon. Uncertainty quantification is given as follows:

1. Uncertainty in water level.

Uncertainty in the digital elevation model is ±7 cm, thus the model can give false results and overestimate or underestimate the results. The greatest deviation from the correct results is for the building polygons that during model calculation are assigned a water level value of 0,1 m, since starting from 0,1 m model assigns damage to a building polygon. In this study case, damage assigned to a building with 0,1 m is 345 eur. For buildings with assigned mean water level > 0,1 m, the deviation is less significant (each next step is around 30 eur more in damage). From the results, water level rise of 0,1 m gives 10x more flooded building polygons, water level rise of 0,2 m gives 25x more flooded building polygons.

2. Uncertainty in building classification.

There can be two sources of uncertainty in building type classification: 1) wrong classification due to the lack of information or too extensive information collection (large areas, no possibility for a field visit) and/or 2) wrong classification due to the uniqueness of a building that does not belong to any category. Depending on the size of the study area, the uncertainty could be in the range of 1-5 %. Regarding this study, the building classification can be assumed fully correct.

3. Uncertainty in depth-damage curves.

While the buildings were classified correctly, the depth-damage curves were assumed and thus did not represent the correct building types. Depth-damage curves from Neubert et al. (forthcoming) gave absolute damage values in the range of -15 – +35% for different building types (345 eur as lowest value and 760 eur as highest value for water level of 0,1 m and 600 eur as lowest and 1010 eur as highest value for water level of 1 m). The developed depth-damage curves are applicable to be used for pluvial flood events, but great uncertainty is introduced since the curves use only few points with damage values and the relevant values were only at water levels 0,1 and 1 m.

4. Model uncertainty.

The model calculates a mean water depth value for each building polygon based on the water depth values as attributes for the 2 x 2 m grid cells that touch the building polygon (both perimeter and area under the polygon). An uncertainty is introduced when for larger building polygons, one side can be flooded, but other side dry (water level = 0), and if the "dry" values are the majority, then the model determines that the building is not flooded at all (see example in Figure 5.2).

Figure 5.3 shows the HOWAD-PREVENT uncertainty quantification.

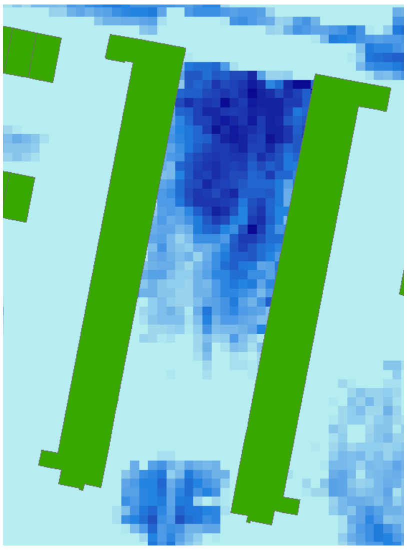

Figure 5.2 Water level calculation in HOWAD-PREVENT (green – no damage)

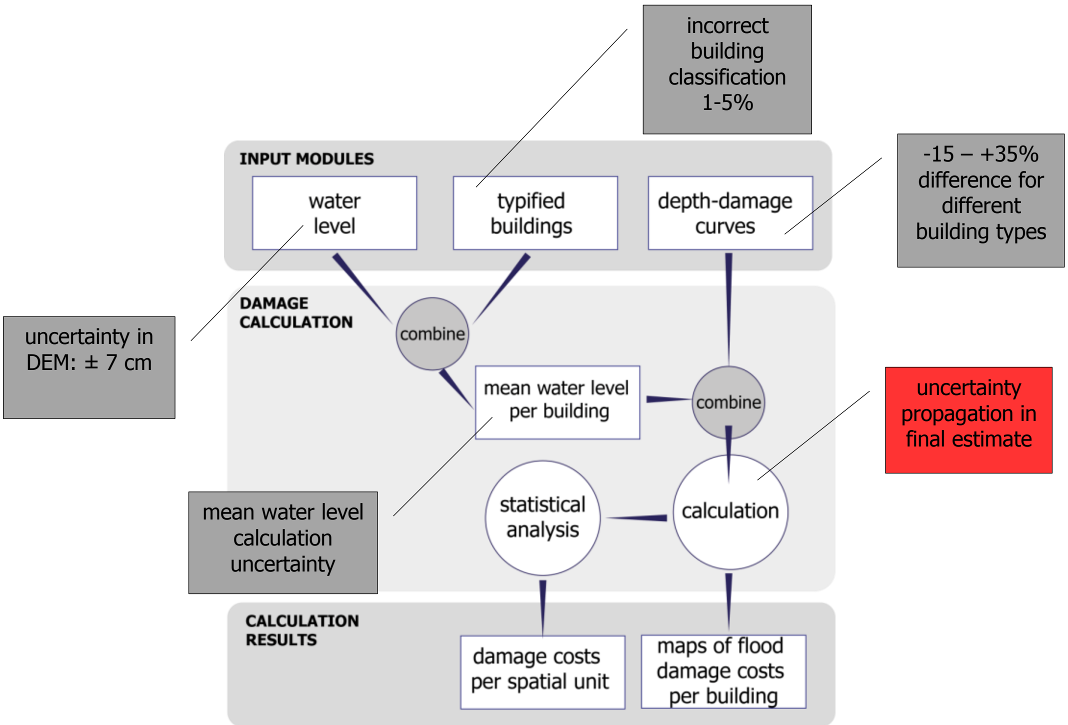

Figure 5.3 Uncertainty quantification in HOWAD-PREVENT

6 Conclusions and recommendations

6.1 Conclusions

After completing the research, an insight was gained in the flood damage modelling uncertainty sources as well as in the functionality of HOWAD-PREVENT when used for pluvial flood damage assessment. The main conclusions of this study are as follows:

- Majority of the studies focus on fluvial and coastal flood damage assessment and the models have been developed accordingly.
- One of the strengths of HOWAD-PREVENT is that the model can be successfully used for pluvial flood damage assessment. The model assigns water level depths for every building polygon with 10 cm steps allowing detailed calculation. The other strength, which at the same time can be weakness, is the detailed approach by using fine water grid and disaggregating buildings into polygons. Weakness stems from the great efforts in data collection. Another weakness of HOWAD-PREVENT is input data uncertainty propagation to the final damage estimate.
- The main uncertainty sources of the HOWAD-PREVENT are all input data sources – water level, building stock classification and depth-damage curves. While building classification has the least influence on the uncertainty, both water level and depth-damage curves have the most influence.
- Assuming that the depth-damage curves used in the model have been created for the specific study area, the greatest uncertainty source in HOWAD-PREVENT is the uncertainty in water levels. 10 cm uncertainty already provides great overestimation or underestimation of the final damage estimate as the damage is allocated to a building polygon, if the mean water level is ≥ 10 cm.
- Specifically for this study, great uncertainty source was the digital elevation model and the method of filling the voids. This combined together with the model concept of using the mean water level value from all grid cells surrounding the building polygon and the cells under the polygon might have caused some buildings to be assigned as flooded, when they should have not been flooded and vice versa.
- Based on the modelling results in the scope of this study, it is not possible to evaluate, if the depth-damage curves used (developed by the model developers) are accurate enough to be used for pluvial flood damage assessment. Validation study should be performed to reach a conclusion.
- More building type combinations should be used (in this study only 2 have been used) in order to assess the difference in model result outcomes if only one averaged depth-damage curve is used for all buildings in the study area instead of several curves for each building type. Unfortunately, information regarding depth-damage curves was one of the limitations for this study.
- As the required water level input grid cells for the model are small (2 x 2 m), water levels surrounded with uncertainty can lead to some buildings being flooded when they are not and vice versa.

- Reduction of epistemic uncertainty requires extensive data collection and time. It is questionable whether this effort corresponds to the gained uncertainty reduction.

6.2 Recommendations

1. Overall

An urban flood event database should be created. A pluvial flood database is absent not only in the Netherlands, but also in UK, where the only known records of the extent and impact of flood events, for example in Heywood, is in the local newspaper reports (Douglas, et al., 2010). Every high water event causing trouble, calls from citizens and nuisance should be recorded following a certain form providing the following information:

- water source (heavy rainfall, fluvial flood, coastal surge, burst water pipe, combination);
- location (neighbourhood, street name, house number);
- date and time;
- type of nuisance (water on the street, water in basement, flooded house, flooded sewer, high ground water level, blocked gully etc.);
- duration (time, how long the water was present on the street, in the house, in the basement etc.).

In addition, a number of affected buildings or number of event observations per area should be set to call the flooding event an event and to register it in a database.

2. HOWAD-PREVENT

- In order to reduce the data collection effort, a realistic maximum possible flood height should be assessed in the study area. If the damage assessment is done for a pluvial flood event and water level is not likely to exceed 1 m, only information regarding ground floor (and basement, if present) is relevant. Some building types can be allocated to one category (for example tall terraced house can be in one building type category as low terraced house, if the only difference between these houses is the number of floors).
- Develop relative depth-damage curves. Now currently developed absolute depth-damage curves can be used in Germany and in neighbouring countries such as the Netherlands because of the similarities in the economic development of these countries and probably also the building stock. Building values and allocated repair costs are expected to be in the same order of magnitude. The modelling effort for projects in these countries can be reduced, because the step of new absolute depth-damage curve creation can be skipped and the existing curves can be used. If other countries would intend to use HOWAD-PREVENT, for example countries in Eastern Europe, where the building costs are different, additional time would have to be spent to create the absolute damage curves. Relative damage curves would be especially useful in case of micro scale assessment.
- Develop depth-damage curves specially for pluvial floods with at least three water levels in the range of 0 – 1 m where damage has been assessed following the procedure described in Chapter 4.
- The proposed building stock analyses method is very time consuming. Semi of fully automated procedures should be developed and used for building type identification. Meinel et al. (2009) has developed a rule-based system for building classification, where buildings and their characteristic parameters are classified by means of "if-then" rules. The following parameters can be automatically mapped on reference geometry (e.g. regular raster): urban block type, number of buildings/development density, building floor area, building volume and other parameters. The automated process has been applied as a toolbox in ArcMap called SEMENTA (Settlement Analyser).

- Consider different building classification approach (relevant for pluvial flooding). The first step would be classification according to the building materials (masonry, reinforced concrete, wooden, other). Then the buildings could be classified based on their vulnerability to inundation following the steps in Figure 6.1.

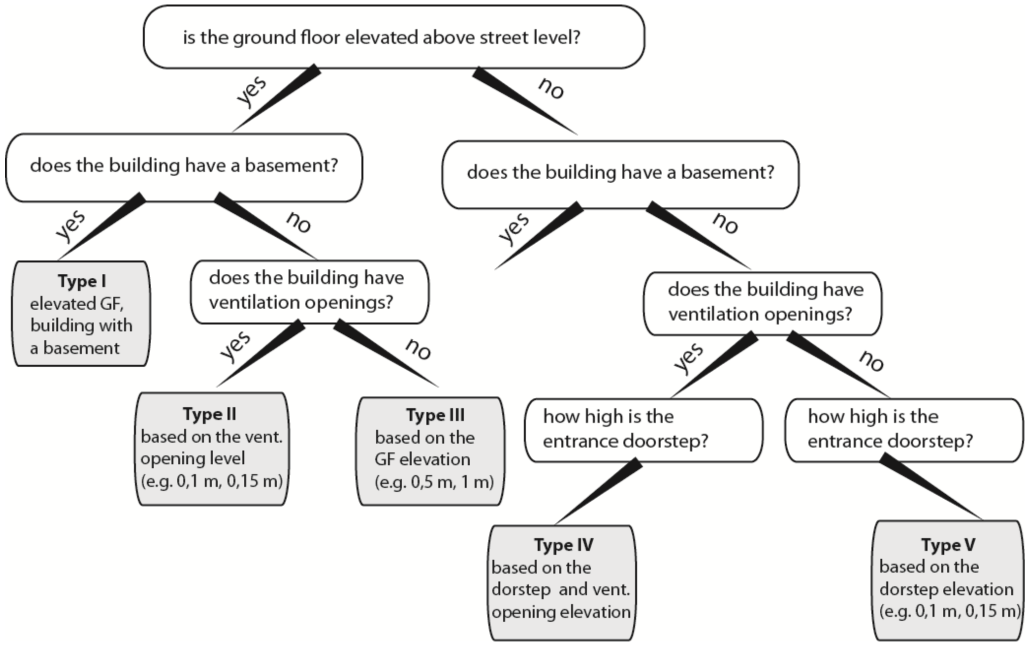

Figure 6.1 Building type classification

3. Model adjustments
   - Is the accuracy gained by having for every building type a detailed representative and own depth-damage curve enough versus the great effort in collecting all the data and creating the curves? In this context investigate, what would be the differences in assessment results, if instead of *n* depth-damage curves, only one, averaged depth damage curve would be used. Using one curve for the area would vastly save the amount of time that is put into the modelling and simplify the model.
   - Compare the model calculation outcome, if for the water level requirement, larger grid cells would be used instead of 2 x 2 m grid cells. The size of the grid cells could vary taking into account the predominant building type in the area. For terraced houses, a grid of 5 x 5 m could be used, for single buildings – 10 x 10 m, for apartment buildings even larger (e.g. 20 x 20 m).
4. Further research
   - Create detailed depth-damage curves taking into account the doorstep, window, and ventilation opening heights on the building wall having more points on the curve for low water depths. For example, entrance to the building can be at the same level as the street, it can have a doorstep (with height of 0,05-0,15 m), the first floor can be located around 1 m above the street level, ventilation openings can be located at various heights on the building wall.
   - Perform HOWAD-P model validation by creating new depth-damage curves that correspond to the study area and compare the results with insurance claim data (where available).

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Appendix

A Flood damage assessment models

A.1 The Netherlands

In the Netherlands flood protection is based on high safety standards. The national law defines protection levels for a number of dike rings with four different safety standards. Coastal and river flooding are two threats that together with the value of assets located in the dike ring, determine which safety standard has to be applied. Economic damage and possible casualties are predicted using the Standard Method which has been developed by HKV consultants and TNO Bouw, supervised by Rijkswaterstaat[16]. The Standard Method is implemented in the HIS–SSM software (HIS=High-water Information System; SSM=Damage and Casualty Module) and the results are mostly used as information for the decision makers on the national and regional level. The "Standard method" considers several asset categories and differentiation is made between direct damage, primary indirect damage, secondary indirect damage (losses occurring outside the dike ring area) and the only intangible damage category – the number of casualties (Bubeck, 2007; Egorova et al., 2008; Meyer & Messner, 2005).

For each location in question, the distribution of objects is determined based on the ground use type. These shape data are combined with the relevant hydraulic characteristics (e.g. the water depth) and are represented on a square grid. For each ground use type, relative damage functions are available. For the use of the HIS-SSM method, a flood scenario must be defined. This scenario is specified by the following hydraulic characteristics: the inundation level, water flow velocity and the rate of water rising. In addition, a protection factor for buildings and the critical water flow velocity at which a building will collapse must be assessed. Another factor that is taken into consideration is whether there is a storm during the flood in question (Egorova et al., 2008).

Table A.1 presents an overview of the HIS-SSM damage assessment method.

Table A.1 Standard method (Egorova et al., 2008; Meyer & Messner, 2005)

Purpose	Coastal and river flooding
Damage categories under consideration	Residential, non-residential buildings, inventory, movable equipment, vehicles, livestock, infrastructure (streets, railways, airports), recreation, agricultural production, traffic disruption, people (casualties)
Spatial scale	Meso, macro
Parameters	Water depth, flood duration (long and short), water flow velocity building type, age, social class of the occupants
Land use data	Several data sources are used depending on the level of detail that is required: CBS[17] for land use, NWB[18] and Spoor NS[19] for infrastructure, Bridgis[20] for household types, Dunn & Bradstreet[21] for the number of employees in each economic sector. All the information collected is transformed to a 100 x 100 m grid for the whole country.

[16] Highway and Hydraulic Engineering Department of the Department of Public Works for the Ministry of Transport, public Works and Water Management
[17] Centraal Bureau voor de Statistiek – Statistics netherlands
[18] National Wegen Bestand – The Dutch national topological road dataset
[19] Nederlandse Spoorwegen – Dutch Railways
[20] Geographic information online
[21] D & B – Business information

Table A.1 Continued

Values of assets	Official statistics and insurance values are used to determine asset values: maximum damage per unit (m^2 of land, meter of street/railway, per flat, per employee).
Damage function derivation	11 relative depth-damage functions are used. Functions are derived from both expert judgment and observed damage data. For residential buildings, additional factors are considered: velocity of inundation and impact of waves caused by storms.
Result	Flood risk for each grid cell (100 x 100 m) as the sum of direct and indirect damage over all damage categories.
Uncertainties	Damage functions are based on historical data and expert judgment, both involves uncertainties. Same depth-damage functions are used for the estimation of indirect losses (inundation depth as an impact parameter might be less suitable regarding losses due to business interruption; duration of flooding might be more appropriate). The method is less suitable for damage assessment on a meso scale due to the degree of averaging.

A.2 England and Wales

Since 1970s, England and Wales have been developing methods for flood damage assessment on different spatial levels for coastal and fluvial floods. Direct or indirect government funding covers nearly all costs for flood defence in England. The Environment Agency has the operational responsibility and the Department for Environment, Food and Rural Affairs has the overall policy responsibility for the flood defence. Standard damage data developed by the Flood Hazard Research Centre (FHRC) is used as basis for damage evaluation in majority of spatial levels. These data have been published in several manuals, starting with the ″Blue manual″ which was the first document to provide guidance on flood hazard evaluation. The "Blue manual" contains information regarding damage to urban properties and for agricultural land. The ″Red manual″ explores indirect effects of floods as well as appraises damage on industrial, commercial and retail flood damages. The ″Yellow manual″ focuses on coastal erosion and coastal flooding. In 2005, the ″Multi-coloured″ manual was produced, which has been updated in 2010 based on recent research and floods that occurred in 2007 in England. The damage evaluation methods focus on direct tangible, indirect and intangible damage (Meyer & Messner, 2005; Middlesex University. FHRC, 2012).

Table A.2 provides an overview of the "Multi-coloured" manual.

Table A.2 Multi-coloured manual (Handmer, 1986; Meyer & Messner, 2005; Penning-Rowsell & Fordham, 1994)

Purpose	Coastal and river flooding	
Damage categories under consideration	Direct tangible: residential, non-residential buildings, household inventory; indirect: losses due to road and traffic disruption, loss of own accommodation, emergency costs, agricultural production loss; intangible losses: health effects, environmental losses.	
Spatial scale	All scales	
Parameters	Water depth (14 levels), flood duration (two classes: long and short), building type, age, social class of the occupants (for the correction of lesser damages).	
Damage function derivation	*Residential:* 1) property classification, 2) depreciated value is determined for the complete building structure and inventory according to replacement costs and market prices, 3) susceptibility of buildings and assets is assessed by loss adjusters.	*Non-residential:* 1) property classification using national property database, 2) asset values and susceptibility to flood for these properties are derived from interviews.

Table A.2 Continued

Values of assets	Tangible direct losses are defined as the difference in value between the pre and post flood condition of damaged items – the damage to structures is the cost of repairs necessary to regain pre-flood condition, damage to contents is valued as the cost of restoration to pre-flood condition (the cost of new items minus depreciation). The cost of new household items (replacement value) is halved to allow for depreciation.	
Land use data	The AddressPoint database (contains location of every property).	Focus database (information about the type of property and its rateable value).
	A merge of both databases: National Property Dataset. In addition, field surveys are carried out to evaluate the type and age for residential buildings and ground floor area for non-residential buildings. The threshold water level (point, where water runs into the building) is estimated for every property, for an exact inundation depth.	
Result	Damage per property	Damage per m^2 of property of certain sector
Uncertainties	Depth-damage data on value change of properties is not being updated frequently enough. Uncertainties exist with regards of future development variables, e.g. impacts of climate change, economic development, land use changes.	

A.3 Czech Republic

In Czech Republic flood damage assessment methods have been developed after major flood events in 1997 and in 2002. General rules for the flood protection policy are formulated in the "Strategy of the flood preventive measures in Czech Republic" by the Ministry of Agriculture. Satrapa (2006) from Czech Technical University developed a three method system for the evaluation of potential fluvial flood losses having different levels of accuracy. One and the same approach is used for all three methods: object-oriented data is used for land use information, values of assets at risk are based on data from official statistics and the damage functions are relative functions. The difference in these methods is the scale they concern. "Method 3" is a detailed method for studies on a local scale, "Method 2" is a simplified version of Method 3 for a regional scale and "Method 1" is a quick method for national level damage assessment. Method 3 is used for verification and validation of the other two methods. There are significant differences between the differentiation of land use – Methods 1 and 2 distinguish between five different building types (residential buildings, industrial buildings and halls, municipal facilities, buildings and halls), while Method 3 recognizes around 200 diverse types of buildings (types, subtypes and construction characteristics) (Meyer & Messner, 2005; Satrapa, 2006).

Table A.3 gives an overview of the Czech methods.

Table A.3 Czech Methods (Satrapa, 2006)

	Method 3	*Method 2*	*Method 1*
Purpose	Fluvial floods		
Damage categories under consideration	Direct tangible: residential, non-residential buildings, inventory, movable equipment, equipment of municipal facilities, infrastructure (streets, railways, bridges, communications), indirect: loss of value added, agricultural production, loss of market positions, intangible: people affected, health.		
Spatial scale	Local	Regional	National
Parameters	Inundation depth, velocity	Inundation depth	Inundation depth
Land use data	Digital topographic data source Zabaged with information on the location and size of buildings, streets; register of economic subjects containing the address and size (number of employees) of each firm, address point data with the number of people and flats per address point.		
	Cadastral maps for information of location and ground floor area of each building. Complete site surveys.	Aggregated land use data source for towns called UPD. Site surveys for special objects.	Generalized version of UPD for districts.

Table A.3 Continued

Values of assets	Value of buildings is estimated by construction cost (full replacement value per m^2) multiplication with the height of each affected floor. Values of technical infrastructure (per m or m^2) and approximate value of household inventory per property are derived from official data (Statistical institute). The equipment costs of municipal facilities (per m^2) are derived from surveys. Value of agricultural production (per ha) is based on production costs for different crops.	
Damage function derivation	Damage functions have been derived synthetically together with information from the last floods. Depth-damage functions are not used for household goods, inventory or equipment; it is assumed that the total value of inventory is lost in case of floods.	
	Each of 200 building-subtypes has its own function	5 different functions for 5 building types considered. Upper and lower susceptibility limits are used to reflect the variety of each class.
Result	Potential losses expressed in thousands of Euros for every damage category under consideration, presentation in maps.	
Uncertainties	Uncertainty bounds: using the minimum and maximum asset value estimations as well as by applying lower and upper limits for damage functions, a minimum and a maximum for the expected flood damage can be estimated.	

A.4 Belgium

Within the national research project ADAPT[22], Dewals et al., (2008) has developed a method to assess the fluvial flood consequences focusing on tangible and direct damages. The aim of this method is to provide tools for selecting and assessing individual flood protection measures. The model analyzes the damages on a micro scale having very high resolution. Contrary to most of the other micro scale models developed, this model does not evaluate object-oriented damages (damage calculated for single assets), but the assessment is performed for a 2 m analysis grid. A land use type is assigned to each mesh included in the simulation. Once the mesh has its land use type, the identification of elements at risk is unnecessary. The validation of the model has been done comparing the results with former observed events.

Table A.4 presents an overview of the method developed by Dewals et al. (2008).

Table A.4 Integrated damage evaluation method (Dewals et al., 2008)

Purpose	Fluvial floods
Damage categories under consideration	Residential, non-residential direct tangible
Spatial scale	Micro scale
Parameters	Water depth
Land use data	Two accurate land use data producers IGN[23] and MET[24] with vector databases Top10v-GIS and PICC respectively. Both databases are used for extraction of the necessary information and for combination in a single data set to identify the assets, land use type and building use.
Values of assets	Land Registry provides information regarding all private properties and the value of the goods (the precision of provided data in the Land Registry is relatively low due to the reason that some data included in this database are old).
Damage function derivation	Relative damage functions are used developed by German FLEMO (Flood Loss Estimation Model)
Result	Relative damage. With additional economic data (estimated value of the assets), the value is generalized at the specific value (value by surface unit). Absolute damage map is computed as the product of the relative damage (%) by the specific value (eur/m^2) defined and by the computational mesh surface (m^2).

[22] "ADAPT - Towards an integrated decision tool for adaptation measures", aimed at developing a decision-support system dedicated to the integrated evaluation of flood protection measures in the context of increased flooding hazard as a result of climate change (Ernst, 2008).
[23] Belgian National Geographic institute
[24] Walloon Ministry of Facilities and Transport

A.5 USA

Federal Emergency Management Agency (FEMA) has developed a software package for natural hazard loss estimation called HAZUS-MH[25]. The model is based on GIS technology and it can simulate four types of hazards: floods, hurricanes, earthquakes and coastal surges. A substantial database is incorporated in the HAZUS consisting of a nationwide inventory of buildings and lifeline systems including buildings and facilities, transportation systems, utility systems, and hazardous materials facilities. In addition, demographic data are included (Schneider, 2006).

The HAZUS flood model is intended to be used by floodplain managers for the support in making informed decisions regarding land use and other issues in flood prone areas. The methodology is comprised from two basic analytical processes: flood hazard analysis and flood loss estimation for a given study area for either riverine or coastal flooding conditions. The flood model is designed to operate at three levels: Level 1 requires minimal user interface and data, Level 2 requires user-supplied data for more detailed analysis and Level 3 analysis yields the most accurate estimate of loss by further modifying building construction and flood damage related parameters based on local conditions. The usage of Level 3 requires expertise knowledge in hydrology/hydraulics, economics, GIS and other fields. The following input parameters are required for the damage model: the building occupancy type, first floor elevation, the depth of flooding at the building area or weighted depth throughout the census block where the building is located. More than 900 depth-damage curves have been provided for structures, contents and facilities (Ding et al., 2008; Scawthorn et al., 2006).

A HAZUS-MH flood model validation study has been carried out by Ding et al. (2008). The author concludes that Level 1 analysis may be appropriate for a quick assessment to locate high flood prone areas, but must be used with caution when used for decision making. Level 2 analysis yields much more reliable loss estimates than Level 1. Another conclusion from this study is that Level 2 estimates for residential damage are more reliable than the outputs from Flood Damage Reduction Analysis (another assessment study performed to acquire results for comparison). At the same time, the loss is overestimated for commercial damage.

Table A.5 gives an overview of the HAZUS-MH flood damage estimation model.

Table A.5 HAZUS-MH flood model (Ding et al., 2008; Scawthorn et al., 2006)

Purpose	Coastal and river floods
Damage categories under consideration	Residential, non-residential buildings, inventory, infrastructure, vehicles, agriculture, shelter needs. Various components are grouped based on similar vulnerabilities and expected loss.
Spatial scale	Meso scale, micro scale
Parameters	Water depth, object type
Land use data	HAZUS-MH does not apply land use data for spatial distribution of asset values, but assumes a uniform distribution of buildings within a census block.
Values of assets	Building asset values are estimated by multiplying the total floor size of a building in a census block with the building replacement costs per ft^2. Depreciated values are derived from data regarding building costs and consider the age and the condition of the structure. Contents asset values are estimated as a fixed percentage of the building asset value.
Damage function derivation	Flood Model uses depth-damage functions for building stock developed by FIA[26] (termed „credibility-weighted" functions) and selected curves developed by various districts of USACE[27]. Damage functions for water, electric and power lines as well as for roads and railroads are developed using combination of historical data and expert opinion. For hospitals, schools and fire stations there is a default damage-curve that can be edited by the user to create a specific function for the corresponding facility.

[25] HAZards U.S. Multi-Hazard
[26] Federal Insurance Administration
[27] U.S Army Corps of Engineers

Table A.5 Continued

Result	Area-weighted estimates for damage as a percent of replacement cost at the census block or for a given building. The estimated percent damage is then multiplied by the total replacement value or the depreciated replacement value to produce estimates of total damage or total depreciated damage.
Uncertainties	Uniform distribution of the buildings within a census block (the smallest unit) is assumed, which leads to another assumption that the asset values also are uniformly distributed. Each census block should cover approx. the same number of inhabitants, so the blocks vary extremely in extent. This variation causes a large error in the spatial distribution of asset values.

A.6 Germany

The competencies of flood and water policy in Germany lie within the individual German federal states and not with the central government. Consequently, the flood damage assessment varies considerably given the different geographical circumstances, various levels of flood hazards and risks in each of the federal states and thus there is no uniform method for damage assessment (Meyer & Messner, 2005).

Damage evaluation studies in Germany have several objectives:

- Prioritization of the flood protection measures,
- Calculation of the share of funding for municipalities for cases, if measures are applied in such a way, that they can be beneficial for more than one municipality,
- Assessment of the efficiency of a single flood protection measure.

All of the methods mainly focus on the assessment of direct, tangible damage categories with an accent to buildings and inventory. Intangible damages are evaluated in quantitative or qualitative terms (Meyer & Messner, 2005).

The flood damage estimation can be carried out on different spatial scales using various sources for the land use data (Büchele et al., 2006):

- Large scale analyses are undertaken for larger land-use units (community, postal code area etc.) and these analyses are often based on the CORINE[28] land cover data, which distinguishes between 45 land-use types.
- Meso scale analysis uses data from ATKIS[29] database, which contains statistical information about population, added values, business statistics and capital assets for land-use units. 100 land-use types are distinguished.
- Micro scale analyses are based on spatial data and depth-damage functions for individual buildings or land parcels. ALK[30] provides information on the base area and specific use of single buildings.

A number of German flood damage assessment methods, such as MURL and Hydrotech (Kreibich et al., 2010), use HOWAS 21 which is an object-specific flood loss database. The database consists of damage cases from various economic sectors: private households (more than 2700 cases), business/industry (more than 2000 cases), agriculture, traffic infrastructure, rivers and hydro-engineering infrastructure (NaDiNe, 2012). Damage functions derived from HOWAS are based only on one parameter – water depth, other flood damage influencing parameters are not considered. These functions are in some cases further evaluated and modified by experts to adapt them to regional settings (Bubeck, 2007).

[28] Coordinated Information on the European Environment
[29] Authoritative Topographic-Cartographic Information System
[30] Automated Real Estate Map

A.6.1 FLEMOps

Flood Loss Estimation Model for the private sector (FLEMOps) uses empirical approach to estimate the flood losses expressed in monetary terms for residential buildings and building contents. The model is based on detailed statistical data analysis from a survey of private households that were affected by the flood in 2002. The loss influencing parameters are classified into four main components: (1) building characteristics (size, type and value of the affected building/contents), (2) household structure (size and age structure), (3) static flood impact (water depth, duration, and contamination) and (4) precaution and flood experience. FLEMOps is a two-stage model. In the first stage, a core model estimates losses according to the water level, building type and building quality. In the second model stage (FLEMOps+), influence of contamination of the floodwater and precaution of private households is considered using scaling factors (Thieken et al., 2005).

The model has been validated for both micro and macro scale. For the validation, the model results were compared to records of eligible repair costs almost representing the building losses (Thieken et al., 2008). Validations of the model have shown that FLEMOps+ outperforms other stage damage functions that are usually applied in Germany (Apel et al., 2009), which confirms the assumption that uncertainty in flood loss estimation can be reduced when more parameters, besides the water depth, are taken into consideration (Merz et al., 2011).

Table A.6 provides an overview of the FLEMOps model. An example of depth-damage curves developed for FLEMOps is presented in figure A.1.

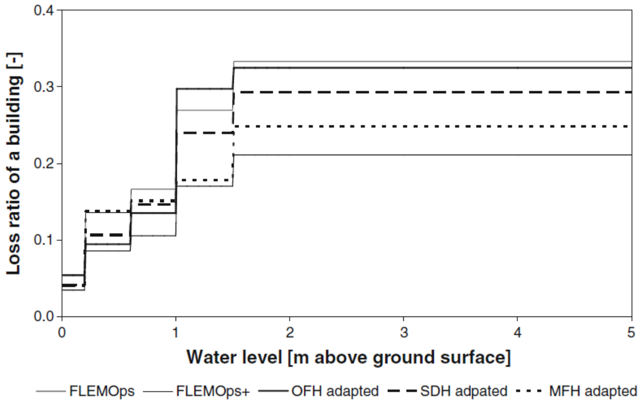


Figure A.1. Meso and micro scale damage functions adapted to the Municipality of Eilenburg (Germany) (OFH – one family house, SDH – (semi-)detached house, MHF – multi-family house)

Table A.6 FLEMOps model (Thieken et al., 2005, 2008)

Purpose	Fluvial floods	
Damage categories under consideration	Residential buildings	
Spatial scale	Micro scale (building-by-building)	Meso scale (land-use units)
Parameters	Water depth (<21 cm, 21-60 cm, 61-100 cm, 101-150 cm, >150 cm), building type (single family, multi family, (semi)detached houses), building quality (low/medium, high), contamination of the flood water (none, medium, heavy), private precaution (none, good, very good). Contamination and precaution are considered, if appropriate information is available.	Building types in clusters: dominated by MFH (multi family house); mixed: high share of MFH; mixed: high share of RDH ((semi)detached house); mixed: high share of EFH (single family house); dominated by EFH.
Land use data		Census data from INFAS Geodaten.

Table A.6 Continued

Values of assets	For buildings, estimated according to Vds guideline. For household contents, estimated following a regression model. Both asset value estimates are in the same order of magnitude as amounts provided by the GDV[31].	The loss ratio (relation between the building/content damage and the corresponding value) is multiplied by the asset value that has been assigned to each grid cell.
Damage function derivation	Damage functions are based on empirical database.	
Result	Damage per building.	Damage for a grid cell.
Uncertainties	Model fails to correctly estimate the building loss at very high water levels.	Error in loss modelling is high and transferability of models to other regions is limited. It is questionable whether loss models that are derived from an extreme flood can be applied to more frequent floods. For loss estimations on large areas building oriented loss functions are often not feasible.

A.6.2 FLEMOcs

Flood Loss Estimation Model for the commercial sector (FLEMOcs) has been designed by Kreibich et al., (2010) in German Research Centre for Geosciences. FLEMOcs is designed to estimate losses to buildings, equipment and goods, products and stock for companies. The model is based on object specific empirical data from three floods in 2002, 2005 and 2006 in Germany. In total, approximately 650 interviews were completed with 220 affected companies using standard questionnaires. In addition, a database of disaggregated asset values is used for the model application at the meso scale (Kreibich et al., 2010).

The model considers four additional factors besides the water level. In a first model stage, it considers the water depth, the size of the company in terms of the number of employees and the sector. In the second model stage, the effects of precaution and contamination are taken into account. The model can be applied at a micro scale, i.e. to single production sites, as well as at a meso scale, i.e. land use units enabling countrywide application (Kreibich et al., 2010; Seifert et al.,2010).

The model has been validated at the micro scale using a "leave one out" cross validation procedure. At the meso scale model results have been compared to the results of official loss records and to the results of other loss models commonly used in Germany, namely MURL, ICPR and Hydrotec (Seifert et al., 2010).

Table A.7 gives an overview of the FLEMOcs model.

[31] Association of German Insurers

Table A.7 FLEMOcs model (Kreibich et al., 2010; Seifert et al., 2010)

Purpose	Fluvial floods
Damage categories under consideration	Commercial buildings, inventory, equipment, products and stock of companies
Spatial scale	Meso scale, micro scale
Parameters	Water depth (5 classes starting from less than 21 cm until more than 150 cm), contamination, indicator for precaution, size of the company (3 classes based on the number of employees: 1-10, 11-100, >100 employees) and sector (4 sectors: public and private services, producing industry, corporate services, trade).
Company classification	Classification into NACE classes according to the statistical classification of economic activities in the European Community.
Values of assets	Firstly, the loss ratios are calculated and secondly, the ratios are multiplied by the monetary (replacement or depreciated) value of exposed assets.
Damage function derivation	Object-specific empirical data from three floods in 2002, 2005 and 2006 in Germany.
Result	Asset values per m^2 for every flooded grid cell (25 m) for the four sectors and three classes of company size. Result is three figures covering losses to buildings and equipment, as well as goods, products and stock.
Uncertainties	Improvements are necessary in some sectors that have very few companies in the database and for very low as well as very high water depths. More accurate land-use data should be used for asset disaggregation.

A.6.3 Damage and loss prediction model (Schwarz & Maiwald, 2008)

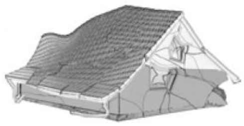
A damage assessment method Schwarz and Maiwald (2008) uses different approach than previously described models. This approach introduces other parameters needed for the assessment, such as global structural Damage Grades (Di), Specific Vulnerability Functions (SVF) and the specific flood vulnerability classes (HW-VC) of a building or object.

By the definition of damage grades (Di), a unified evaluation of all damaged objects can be achieved. Five damage grades, classified in order of increasing flood impact, each summarize the main criteria for the classification of observed effects and damage reports and can be seen in Table A.8. Buildings of different structural type and material belong to the same vulnerability class, if for the relevant range of flood action parameter, similar mean damage grades have to be expected. The damage reports are based on surveys after flood events in August 2002 and floods in 2005 and 2006 in Germany.

Five Flood Vulnerability Classes (HW-A to HW-E) are distinguished, covering the range from low flood resistance/higher vulnerability (A - very sensitive; B - sensitive), to normal (C) and increased flood resistance (D). A flood resistant design would lead to the class (HW-E). Class HW-E buildings are characterized by a separation of building from the flood water table, for instance, by "up-lifting" the base floor. The flood vulnerability class is assigned to buildings based on their type (clay, prefabricated, masonry, framework, reinforced concrete, flood resistant design) as shown in Figure A.2.

A new type of damage functions – specific vulnerability functions – have been developed for this method. The functions link the inundation level (in m) to the assigned damage grade. These functions differ for every vulnerability class. An example is presented in Figure A.3. The model results indicate a good agreement between the predicted and the reported losses.

Table A.8 Assignment of damage grades Di to damage cases (Schwarz & Maiwald, 2008)

Di	Structural damage	Non-structural damage	Description	Drawing
D1	no	slight	only penetration and pollution	
D2	no to slight	moderate	slight cracks in supporting elements; impressed doors and windows; contamination; replacement of extension elements	
D3	moderate	heavy	major cracks and / or deformations in supporting walls and slabs; settlements replacement of non supporting elements	
D4	heavy	very heavy	structural collapse of supporting walls, slabs; replacement of supporting elements	
D5	very heavy	very heavy	collapse of the building or of major parts of the building; demolition of building required	

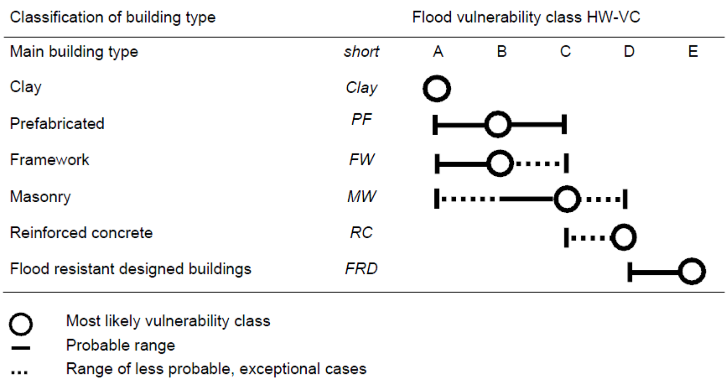


Figure A.2 Classification of building types in vulnerability classes and identification of ranges of scatter (Schwarz & Maiwald, 2008)

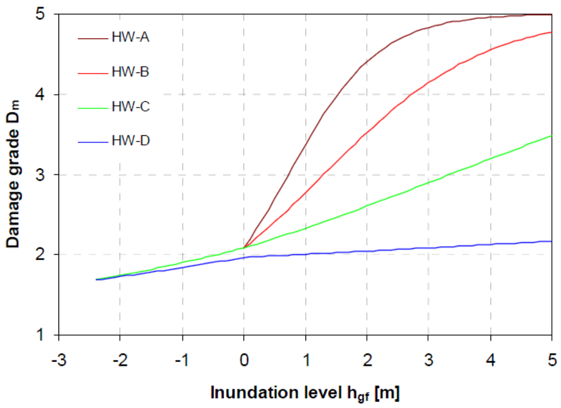


Figure A.3 Specific Vulnerability Functions (Schwarz & Maiwald, 2008)

B Modelling results

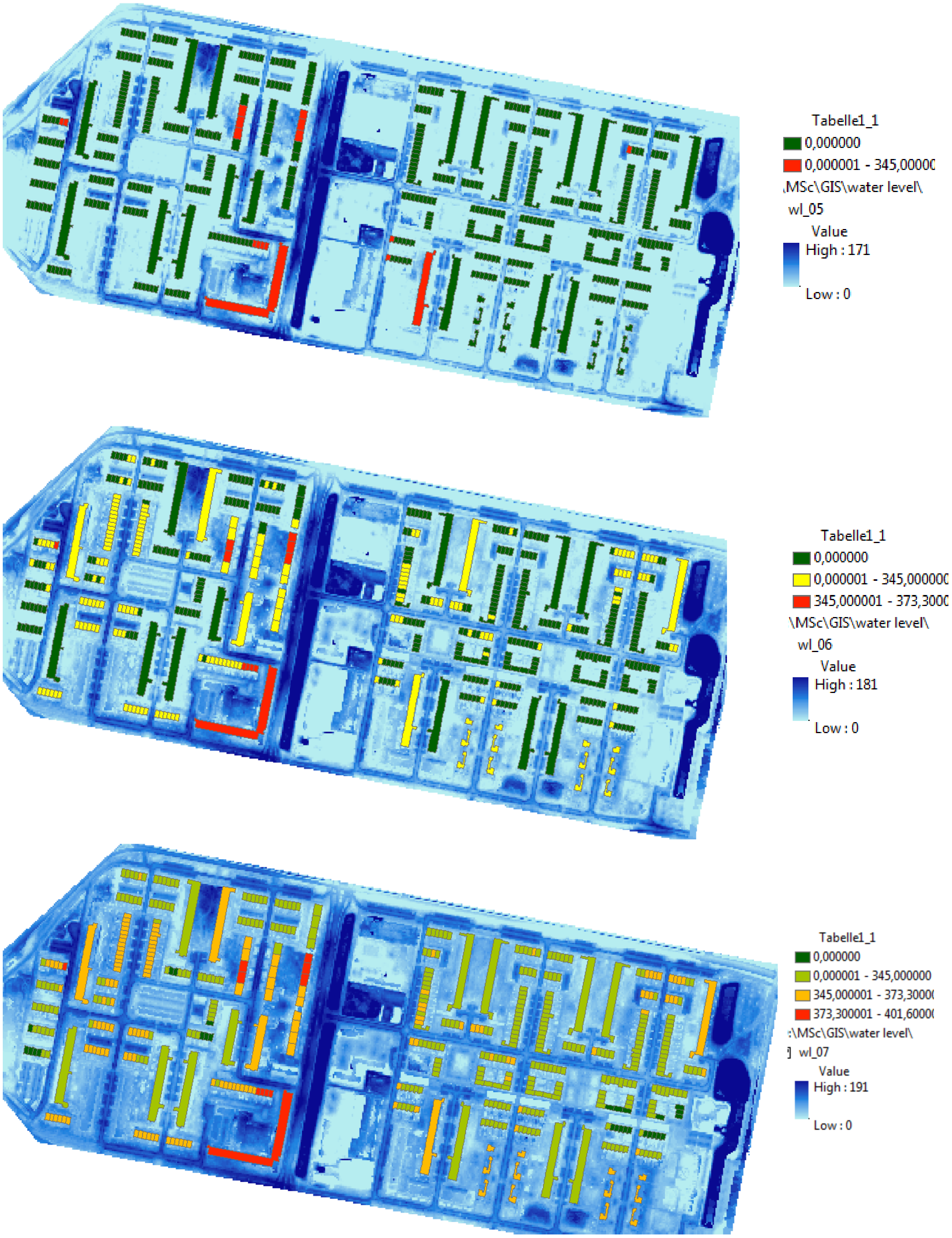


Figure B.1 Damage per m²
Top: +0,5 m (run no. 1), middle: +0,6 m (run no. 2), bottom: +0,7 m (run no. 3)

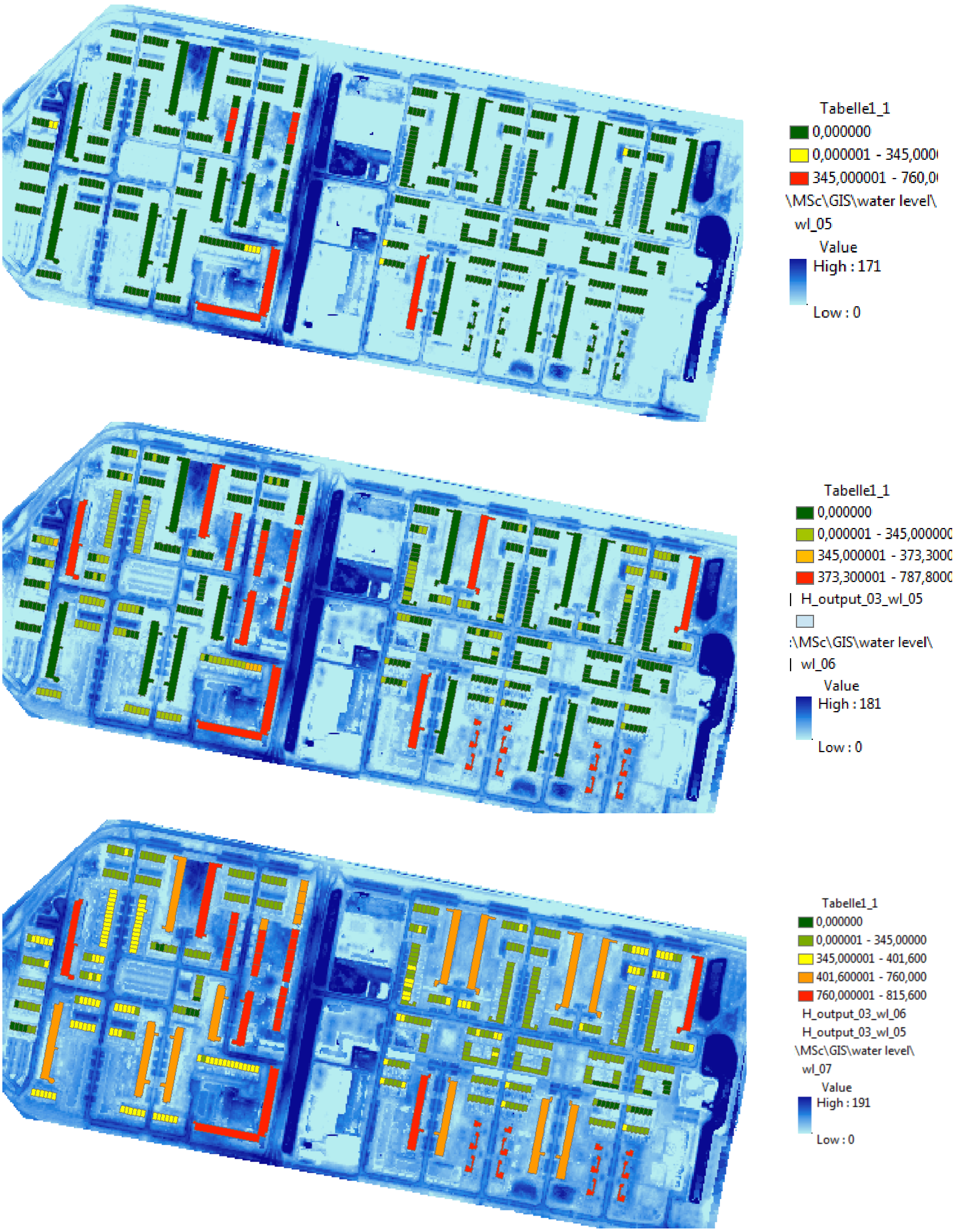


Figure B.2 Damage per m²
Top: +0,5 m (run no. 4), middle: +0,6 m (run no. 5), bottom: +0,7 m (run no. 6)

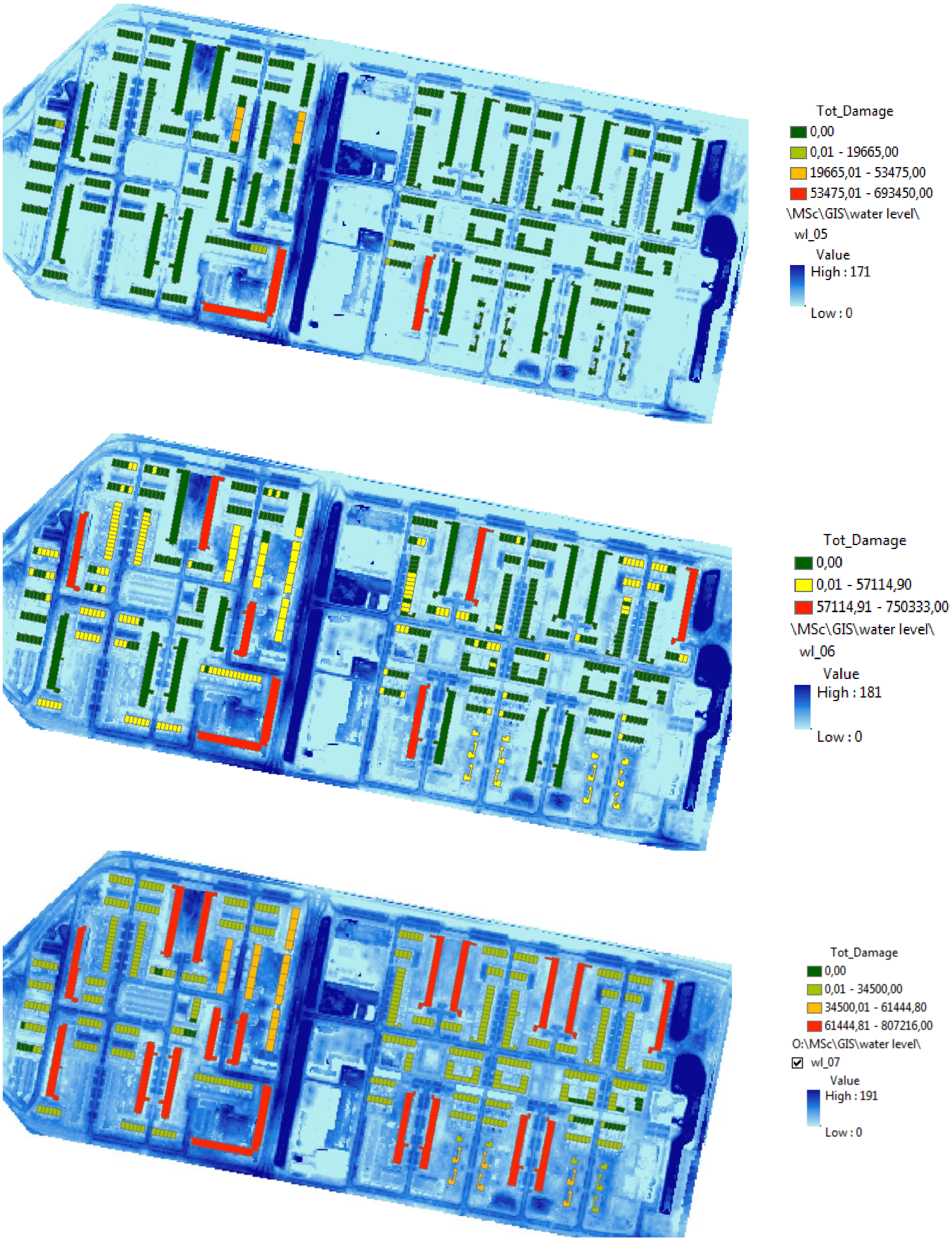


Figure B.3 Total damage per building polygon
Top: +0,5 m (run no. 1), middle: +0,6 m (run no. 2), bottom: +0,7 m (run no. 3)

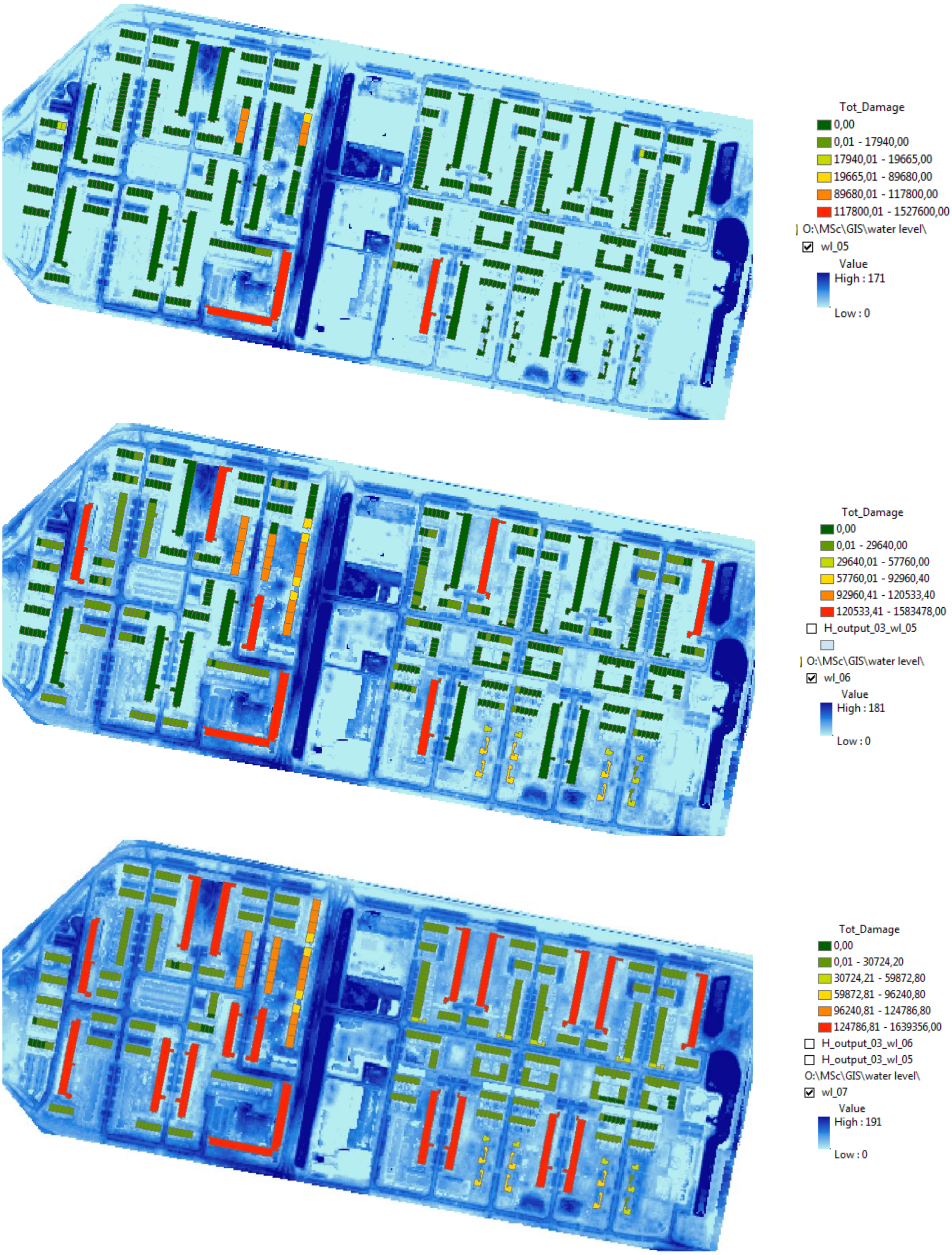


Figure B.4 Total damage per building polygon
Top: +0,5 m (run no. 4), middle: +0,6 m (run no. 5), bottom: +0,7 m (run no. 6)

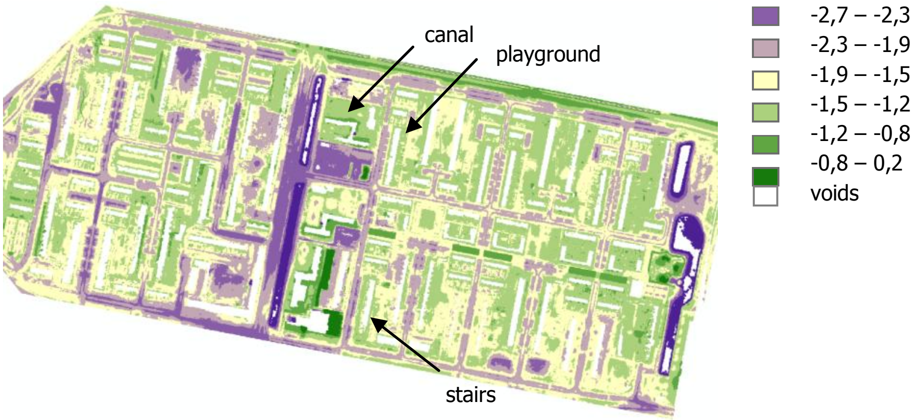
C Input data collection protocols

Water level

GIS processing scheme:

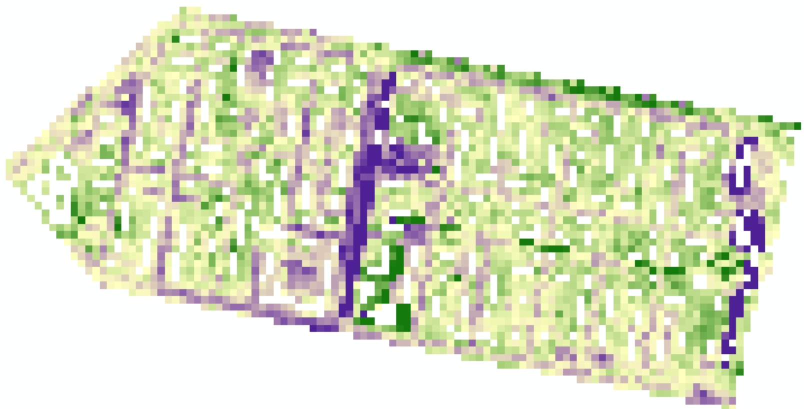
(1) Choosing the deepest point in the study area based on visual observation and a Box plot: View → Graphs → Box plot. It is important to have knowledge of the area (site visit, Google maps or Bing maps street view) to be able to exclude errors, noises or other inadequate values.

The deepest point of this study is the edge of a canal: -1,80 m.



(2) As the DEM has been filtered (buildings, trees, cars are not included in the image, instead, blank spaces are present), the voids have to be filled with values. This can be done using Kriging[32] method:

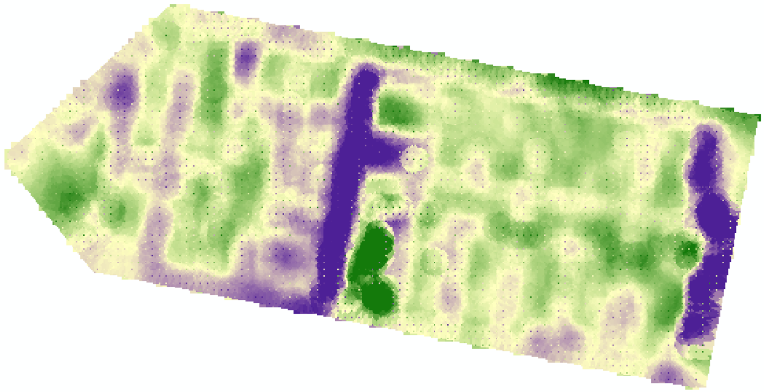
a. Resize the pixels of the map in Step 1 (original size 0,5 x 0,5 m) to a greater value: Data management tools → Raster → Raster Processing → Resample (output cell size = 10, resampling technique: nearest)



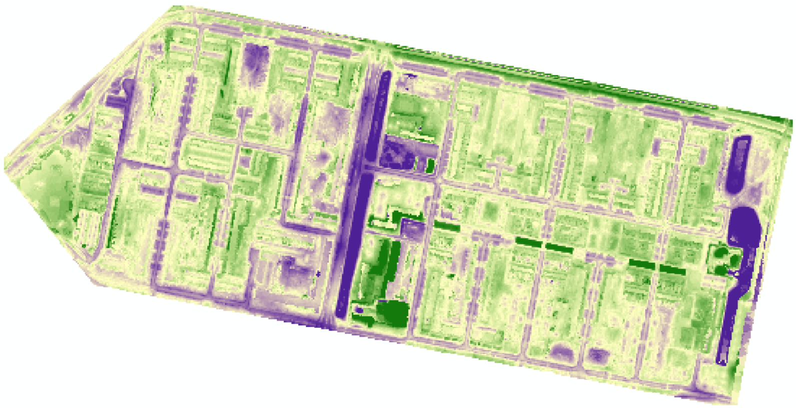
[32] Kriging – a technique to interpolate the value of a random field at an unobserved location from observations of its value at nearby locations.

b. Assign a point to every pixel to the map of Step 2a:
Conversion tools → From Raster → Raster To Point

c. Apply Kriging to the map of Step 2b:
3D Analyst → Raster Interpolation → Kriging (Z value = GRID_CODE, Model = Gaussian, Method = Ordinary, Output Cell Size = 2)



(3) As the objective was to fill in the voids with values, the other values (in the vicinity of buildings) must be cropped. The original ground level values are put in one file together with the results of Kriging:
Spatial Analyst → Map Algebra → Raster Calculator (Conditional expression = *Con(IsNull("map_Step_1"), "map_Step_2c", " map_Step_1")*)



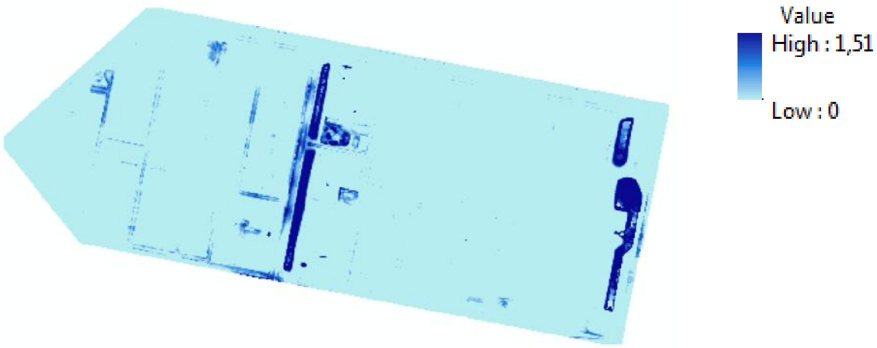
(4) The study case area is located below the mean sea level, thus having negative height values, the map has to be "virtually lifted". At the same step, a water level situation A is executed – 0,3 m of water level is added to the lowest point in the area:
Spatial Analyst → Map Algebra → Raster Calculator (Expression = *0.3 - ("map_Step_3" + 1.8)*)

To have positive flooding values only (negative values are seen as groundwater flooding in HOWAD-P), the following step has to be performed:

Spatial Analyst → Map Algebra → Raster Calculator (Expression = *Con(("map_Step_4" < 0), 0, " map_Step_4")*)

The raster set has to be exported to a GRID extension and multiplied by 100 using the Raster Calculator in order to have the water level values in cm:

Export Raster Data → GRID



D Building types in the study area

Type	Description	Photo
TH I	- Construction in 1999 - Building materials: bricks - Number of floors: 2 - Cellar use: no cellar - Doors: wooden doors 0,15 m above street level - Ventilation openings 0,05-0,1 m above street level - Wall construction: unknown	
TH II	- Construction year unknown - Building materials: bricks - Number of floors: 2-3 - Cellar use: no cellar - Doors: wooden, 0,05-0,15 m above street level - Ventilation openings: 0,15-0,2 m above street level - Windows: types B and C have large windows ~0,05 m above street level - Wall construction: unknown	
TH III	- Construction in 2008 - Building materials: bricks - Number of floors: 2 + attic - Cellar use: no cellar - Doors: - front – wooden doors 0,05 m above street level - back – wooden doors and tall windows - Ventilation openings 0,05 m above street level - Wall construction: unknown	
TH IV	- Construction in 1994 - Building materials: bricks - Number of floors: 2 - Cellar use: no cellar - Doors: front – wooden doors 0,1 m above street level back – wooden doors, or tall windows 4/5 of the wall's surface - Ventilation openings 0,1 m above street level - Wall construction: unknown	

TH V

- Construction year unknown
- Building materials: bricks, concrete
- Number of floors: 2-3
- Cellar use: no cellar
- Doors: wooden doors 0,05m above street level
- Back of the building: window cowering all wall surface
- Ventilation openings 0,25 m above street level
- Wall construction: unknown

TH VI

- Construction is 1998
- Building materials: bricks
- Number of floors: 3
- Cellar use: no cellar
- Doors: wooden doors 0,1 m above street level
- Back of the building: brick wall around terrace
- Ventilation openings 0,1 m above street level
- Wall construction: unknown

MRO I

- Renovated in 2001
- Building materials: bricks, concrete
- Ground floor use: storage, entrance, stairs, no living space
- Cellar use: no cellar
- Doors: glass entrance doors/windows, wooden storage entrance doors
- Wall construction: unknown

MRO II

- Construction in 1996
- Building materials: bricks, concrete
- Ground floor use: flats, 1,09 m above street level
- Cellar: cellar with vents, 2,5 m below ground floor, first 3 and last 3 sections have cellars
- Wall construction: unknown

MRO III
MRO V

- Construction in 1998
- Building materials: bricks, concrete
- Ground floor use: flats, ~1,3 m above street level
- Cellar: cellar with vents
- Wall construction: unknown

MRO IV
MRO VI
- Construction year unknown
- Building materials: bricks
- Ground floor use: flats, ~0,7-0,8 m above street level
- Cellar: cellar with vents at the back of the building, windows to cellar in the front of building
- Wall construction: unknown

MRO VII
- Construction year unknown
- Building materials: bricks, concrete
- Ground floor use: flats, ~0,8-1 m above street level
- Cellar: no cellar
- Wall construction: unknown

MRO VIII
- Construction year unknown
- Building materials: concrete
- Ground floor use: flats, ~0,8 m above street level
- Cellar: cellar with vents
- Wall construction: unknown