Kreibich, H., Thieken, A. H. (2008): Assessment of damage caused by high groundwater inundation. - Water Resources Research (AGU), 44, W09409,

DOI: 10.1029/2007WR006621

*Accepted for publication in Water Resources Research*

# Assessment of damage caused by high groundwater inundation

Heidi Kreibich, Annegret H. Thieken

GeoForschungsZentrum Potsdam (GFZ), Section Engineering Hydrology, Potsdam, Germany

Correspondence to:

Dr. Heidi Kreibich

GeoForschungsZentrum Potsdam

Section Engineering Hydrology

Telegrafenberg C4

D-14473 Potsdam

Germany

Tel. +49-331-288-1550

Fax. +49-331-288-1570

e-mail: kreib@gfz-potsdam.de

**Abstract**

In several cities around the world, problems with rising groundwater levels were reported, but up to now, losses caused by high groundwater levels have been neglected in loss assessment studies. However, reliable loss assessments are necessary to evaluate the cost-effectiveness of mitigating measures like groundwater withdrawal and drainage. To improve the knowledge about flood losses and the loss-influencing factors, 1697 households affected by the Elbe and Danube floods in 2002 in Germany were interviewed. Cases affected by a high groundwater level were identified and analyzed in comparison with cases affected by riverine flooding. Inundations due to high groundwater show significantly different impact and damage characteristics in comparison with riverine floods. Most common loss models tested were as such not suitable to estimate losses due to high groundwater. Therefore, new loss models have to be developed. One step in this direction is the development of loss models just on basis of loss data from groundwater flooding. From all such models tested, the multifactorial model FLEMOps+ performed best, confirming that the uncertainty in loss estimation can be reduced if more predictive variables, besides the water level, are taken into consideration. However, further research is necessary to investigate the main factors influencing the losses due to groundwater flooding and to develop specific models for their assessment.

**Key words:** High groundwater, flood impact, flood damage, vulnerability, damage estimation, loss modeling

**Index terms:** Anthropogenic effects, Floods, Human impacts, Groundwater/surface water interaction

## 1. Introduction

The economic losses due to floods have dramatically increased during the last decades, which emphasizes the need to improve flood risk management. To reduce future flood losses in a sustainable manner, flood risk management has to be built upon a sound analysis and assessment of the flood hazard, potential losses and the effectiveness of different mitigation measures. In fact, risk analyses and risk-oriented design, in which the cost-effectiveness of flood defense schemes is evaluated, are gaining more and more attention in water and planning agencies [e.g. *Resendiz-Carrillo and Lave*, 1990; *USACE*, 1996; *Olsen et al.*, 1998; *Al-Futaisi and Stedinger*, 1999; *Ganoulis*, 2003; *Rose et al*., 2007]. Moreover, risk analyses quantify the risks and thus enable communities and people to prepare for disasters [e.g. *Takeuchi*, 2001; *Merz and Thieken*, 2004]. However, some aspects of flood risk analysis and management have not received much attention by now. Especially, the analysis and modeling of flood losses is an area which does not receive much attention [*Wind et al.*, 1999] and where not many empirical data exist.

Hardly any study investigates the damage due to inundations caused by high groundwater levels. However, reliable loss assessments are necessary to evaluate the cost-effectiveness of measures like groundwater withdrawal and drainage, the construction of rain, surface and floodwater collection networks or the enhancement of sewerage collection systems, networks and subsurface storages [*Hagerty and Lippert*, 1982; *Hamdan and Mukhopadhyay*, 1991; *Al-Sefry and Sen*, 2006].

The present study is limited to the analysis and estimation of direct flood losses to residential buildings and contents caused by high groundwater levels triggered by riverine floods. The objective of the study is to characterize the flood impact and the resulting losses to residential buildings and contents due to high groundwater levels. Importantly, implications for the estimation of losses due to high groundwater are discussed and different loss models are tested. A promising approach how to develop reliable loss models for the estimation of losses due to groundwater flooding is presented.

## 2. Literature review

### 2.1 Causes of high groundwater levels

In general, problems with high groundwater levels mainly occur in floodplains or low-lying areas. Usually, building construction is adapted to the average groundwater level, i.e. in low-lying areas buildings are often constructed without basements. 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 into the aquifer or a reduced withdrawal of groundwater (Figure 1).

High infiltration might be due to heavy precipitation and riverine floods [*Hardt and Hutchinson*, 1978; *Vekerdy and Meijerink*, 1998; *Landeshauptstadt Dresden*, 2005] or anthropogenic activities [*Hardt and Hutchinson*, 1978; *Hamdan and Mukhopadhyay*, 1991; *Al-Sefry and Sen*, 2006]. For instance, during the flood in 2002 in Germany, 240 properties of the federal state of Saxony were flooded resulting in a loss of €183 million. 16% of the losses were caused by high groundwater levels [*Huber et al.*, 2003]. Particularly, historic buildings were not designed for high groundwater levels and the resulting buoyancy. Thus their basements had to be flooded to avoid heavy structural damage.

In 2002, the federal state capital Dresden was highly affected by groundwater problems since the groundwater rose rapidly and partly up to the surface and stayed at a very high level for several months. The emergency measures to save the highly endangered sports hall of the St. Benno grammar school and an adjacent transformer room in Dresden were quite sensational: The base plate of the hall had been lifted for more than 20 cm due to the rising groundwater. At the maximum groundwater level, the buoyancy at the plate was about 14.7 kN/m² [*Beyer*, 2003]. Extensive on-site investigations as well as perusing of expert reports and building files were necessary to decide on suitable measures. More than 500 volunteers brought sandbags and quick-dams filled with water into the hall to increase the necessary counter pressure. The transformer had to be switched off, leading to a lack of electricity at the school and the adjacent residential area [*Beyer*, 2003]. The emergency measures were successful, and building precautionary measures have been undertaken after the event, to be prepared for future groundwater flooding.

In arid and semiarid areas, water supply form distant areas or through desalination plants may cause a significant rise of the groundwater level [*Hardt and Hutchinson*, 1978; *Hamdan and Mukhopadhyay*, 1991; *Rushton and Al-Othman*, 1994; *Al-Sefry and Sen*, 2006] which is illustrated by the following three examples: Basin replenishment by artificial recharge of imported northern California water at the base of the San Bernardino Mountains caused a groundwater level rise in the 1970's in the highly urbanized city of San Bernardino that was formerly swampy land. It was feared that the renewed flowing of unplugged artesian wells, which are buried beneath buildings and roads damage buildings, public works and utilities [*Hardt and Hutchinson*, 1978]. In Kuwait City, the addition to the aquifer storage due to the contribution from man-made sources like seepage from septic tanks, leakages from sewerage systems and water distribution networks and irrigation caused a subsurface-water-level rise locally of about 5 m over the period 1961-1985 and about 2.5 m between 1985 and 1990 [*Hamdan and Mukhopadhyay*, 1991]. Thus, the residential areas of Kuwait City were affected by water logging and flooding of basements [*Hamdan and Mukhopadhyay*, 1991]. Similar causes lead to high groundwater levels resulting in an inundation of low-lying areas between 1996 and 2002 in the city of Jedddah, Kingdom of Saudi Arabia [*Al-Sefry and Sen*, 2006]. Damage caused were the flooding of basements, deterioration of roads, damage to building foundations, the contamination of soil, offensive smell and breeding of mosquitoes [*Al-Sefry and Sen*, 2006]. In several cities in industrialized countries, e.g. Louisville, London or Birmingham, the reduction in the rate of groundwater withdrawal lead to an accelerating rise of the groundwater level since the 1960's, when the demand dropped significantly with the decline of heavy industry and as industries moved out of city centers [*Hagerty and Lippert*, 1982; *Johnson*, 1994; *Gallagher and Brassington*, 1994; *Greswell et al*., 1994].

2.2 Damage due to high groundwater levels

In general, damage is classified into direct and indirect damage. Direct damage occurs due to the physical contact of (flood) water with humans, property or any other objects. Indirect damage is induced by a flooding, but occurs, in space or time, outside the actual event. Usually, both types of damage are further classified into tangible and intangible damage, depending on whether or not they can be assessed in monetary values [*Smith and Ward*, 1998]. In this context, property damage that is caused by high groundwater levels, which accompany a riverine flood, are direct, tangible flood losses. Although it is acknowledged that direct intangible damage (e.g. health problems) or indirect damage (e.g. long-term drop in building prices due to groundwater problems) play an important or even dominating role in evaluating flood impacts [*FEMA*, 1998; *Penning-Rowsell and Green*, 2000] these damage categories are neglected here.

The type of property damage due to high groundwater levels to residential buildings and contents differs depending on whether or not the water enters the building (Figure 2). Additionally, the presence or absence of contamination of the groundwater makes a difference. Groundwater may enter the building subsurface through permeable basement floors/walls or openings for service pipes. Since high groundwater levels decrease slowly [*Landeshauptstadt Dresden*, 2005], the water might stay in the building for several weeks, if the basement cannot be sealed or the groundwater level cannot be lowered. Even wall areas above the groundwater level might be damaged due to capillary rise [*Kelman and Spence*, 2004]. Highly affected are building materials and contents which are susceptible to water, e.g.

wooden floors or paneling are easily destructed by water. In contrast to carpeted floors, tiled floors reduce household losses to a great extent [*Yeo*, 2002].

Since mainly only basements are affected by rising groundwater, the losses depend strongly on the fixtures and the use of the basements. For instance, it is important whether heating and other building services are located in the basement or in higher stories and whether they are flood-proofed or not [*FEMA*, 1999]. Flood adapted building use means that basements are not used cost-intensively (e.g. as living or business rooms) and no expensive upgrading is undertaken. For instance, installing a sauna or a high tech hobby room in the basement should not be an option [*Kreibich et al.*, 2005]. To avoid the problem of high groundwater entering the building, building without a basement, or water proof seal the basement should be considered for new buildings. Additionally, any openings in the building must be raised or sealing measures must be implemented. Buildings are sealed by using bitumen or strips of plastic [*Environment Agency*, 2003] or by constructing the basis and walls of buildings out of concrete that is almost non-permeable [*BMVBW*, 2002]. However, water should only be kept out of the buildings as long as they are stable. If the water level continues to rise, the building must be flooded with clean water.

If chemicals or non-flood-proofed fuel tanks are stored in the basement, flooding may cause contamination of the inflowing groundwater which may aggravate the damage of the building. Detailed descriptions of chemical and biological actions as well as other flood actions on buildings were published by *Kelman and Spence* [2004]. Widespread contamination of the groundwater may be caused if the high groundwater affects brownfields or leakages in the sewer system [*Landeshauptstadt Dresden*, 2005]. Problems of corrosion and deterioration of foundation material are related to the groundwater quality [*Al-Sefry and Sen*, 2006]. Therefore, an important mitigation measure is the safe and secure storage of oil and other hazardous substances, e.g. in flood-proof fuel oil tanks [*ICPR*, 2002]. Also small private sewage treatment plants must be protected against flooding. Tanks can float when the flood water level rises and can be damaged by water pressure. High groundwater levels may affect the stability of building foundations through buoyancy and increasing pore pressure [*Morrison and Taylor*, 1994; *Landeshauptstadt Dresden*, 2003]. Counter measures that can be undertaken include anchoring the building or ensuring that the building itself is heavy enough. Only if the buoyancy forces surpass the effect of these measures, the building has to be flooded. A variety of building precautionary measures against floods were analyzed by *Kreibich et al*. [2005].

2.3 Flood loss estimation

A central idea in flood loss estimation is the concept of loss functions, e.g. stage-damage curves. Most loss models have in common that the direct monetary damage is obtained from the type or use of the building (i.e. residential, commercial, etc.) and the inundation depth [*Smith*, 1981; *Wind et al*., 1999; *NRC*, 2000; *Green*, 2003; Penning-Rowsell et al., 2005]. Such stage-damage functions are internationally accepted as the standard approach to assess urban flood losses [*Smith*, 1994]. For Germany, some stage-damage curves are published by *Buck and Merkel* [1999] and *Büchele et al*. [2006].

Probably, the most comprehensive approach has been the “Multi-Coloured Manual” and its precursors that contain stage-damage curves for - among others - 28 typical dwelling types in the UK [*Penning-Rowsell and Chatterton*, 1977; *Penning-Rowsell et al*., 2005].

A considerable amount of work about flood loss estimation has also been done in the USA. Risk-based evaluation was early proposed by the US Army Corps of Engineers (USACE, 1996) and was accompanied by the development of the software package HEC-FDA, the Flood Damage Analysis program (*HEC*, 1998). In addition, the new HAZUS model was released by the Federal Emergency Management Agency (FEMA) in 2004. Originally, only capable of modeling earthquake loss, the latest version of HAZUS-MH (MH stands for multi-hazard) also includes tools for flood and wind loss estimation, runs on a ArcGIS platform and provides default data so that standardized risk assessment can be performed [*Beckmann and Simpson*, 2006; *Rose et al.*, 2007].

It is obvious that flood loss depends, in addition to building type and water depth, on many factors, such as flow velocity, duration of inundation, sediment concentration, availability and information content of flood warning, and the quality of external response in a flood situation [*Smith*, 1994; *Penning-Rowsell et al.*, 1994; *USACE*, 1996; *Nicholas et al*., 2001; *Kelman and Spence*, 2004; *Kreibich and Thieken*, 2008]. A few studies give quantitative hints about the influence of some factors [*McBean et al*., 1988; *Smith*, 1994; *Wind et al*., 1999; *Penning-Rowsell and Green*, 2000; *ICPR*, 2002, *Kreibich et al*., 2005; *Thieken et al.* 2005; *Penning-Rowsell et al*., 2005]. Recently, models that consider more parameters besides the water level were introduced. For example, *Zhai et al*. [2005] developed a multivariate regression model with inundation depth, home ownership, house structure, length of residence and household income to estimate losses in private households. Thieken et al. [2008] present the new flood loss estimation model FLEMOps. It estimates direct economic flood losses for the residential sector and works in two stages. The basic model stage estimates the loss on the basis of water depth, building type and building quality. In an additional model stage, the effects of private precautionary measures as well as of the contamination of the floodwater can be considered. However, there is no loss model available which take different flood types, e.g. groundwater flooding, flash floods, riverine flooding, into account.

## 2. Data and methods

To improve the knowledge about flood losses and the loss-influencing factors, 1697 households affected by the Elbe and Danube floods in 2002 in Germany were interviewed. Lists of all affected streets were comprised with the help of official data and building specific random samples of households were generated. Computer-aided telephone interviews were undertaken with the VOXCO software package by the SOKO-Institute, Bielefeld, Germany. Always the person with the best knowledge about the flood damage was interviewed. Tenants were only asked about their household contents and relevant precautionary measures. To complete the interview the building owner was asked about the building and retrofitting measures. The interviews were undertaken in April and May 2003 in the most affected German federal states: Saxony, Saxony-Anhalt and Bavaria (Figure 3). The questionnaire contained about 180 questions addressing the following topics: flood impact (i.e. water level, duration, flow velocity, contamination), flood warning, emergency measures, evacuation, cleaning-up, characteristics of and losses to household contents and buildings, recovery of the affected household, precautionary measures, flood experience as well as socio-economic variables. Detailed descriptions of the survey and the data processing were published by *Kreibich et al*. [2005] and *Thieken et al*. [2005, 2007a]. A flow velocity indicator was developed based on information about deposited material, water levels, two qualitative velocity assessments, flood types, damage to the building fabric and the way the water intruded the building [see *Thieken et al*., 2005]. The indicator contains the values: 0 = stagnant, 1 = moderate, 2 = high, 3 = very high flow velocity. Further, an indicator for the contamination of the flood water was introduced, with values from 0 = no, 1 = medium and 2 = high contamination (i.e. multiple contamination including oil or petrol).

Further, the surveyed monetary losses were transformed into loss ratios i.e. the relation between the building/content loss and the corresponding asset value, were calculated. For this, the total asset values of the affected buildings were estimated according to the VdS guideline 772 1988-10 [*Dietz*, 1999], which is commonly applied in German building insurance. The total replacement values of the household contents were estimated using a regression model that depends on the living area of the household and the purchasing power relevant to retail trade in the postcode, where the household is situated [see *Thieken et al.*, 2005, for details].

Interviews were identified as cases affected only by a high groundwater level, if people stated that 1) the water entered their building only from below and the water level was at maximum 50 cm (above the ground surface) or 2) the water entered their building from outside and below, but the main inundation source was groundwater and the water level was at most 50 cm (above the ground surface). According to these criteria, 264 interviewed households were identified as affected by high groundwater only. In the cases where households were at the same time affected by high groundwater and a riverine flood it is impossible to differentiate the flood impact and losses due to the two flood types. These cases are included in the "riverine flood group", since this is commonly the dominating process. Thus, the remaining 1433 interviewed households were classified as affected by riverine floods. This group is, however, quite heterogeneous, since it also contains other flood types such as flash floods and inundations due to levee breaches. This is demonstrated by a cluster analysis which was performed with the four impact variables, i.e. water level, flood duration, flow velocity indicator and indicator for contamination to find groups with similar flood impact (Ward-Algorithm with squared Euclidian distance) [*Thieken et al.*, 2007b]. Thus, for a more consistent comparison between riverine floods and groundwater flooding, only riverine flood cases with water levels up to 50 cm were used.

Significant differences between two independent groups of data (e.g. flood types) were tested by the Mann-Whitney-U-Test [*Norušis*, 2002]. A significance level of $p < 0.05$ was used. To analyze the performance of different loss models, a split sampling technique was applied [*Klemes*, 1986]. The database with 1697 interviews was split into two equal parts as the datasets were put into the chronological order of undertaken interviews and every other was singled out. Thus, two sub-datasets were formed with 849 and 848 datasets, respectively. In a first step, loss models were developed on the basis of the first subset and were applied to the second subset, irrespective of the flood type. The second step was vice versa: Loss models were derived from the second subset and were applied to the first. The following three types of loss models were tested, listed in the order of increasing complexity:

First, models taking into account the water level as the only predictive variable, i.e. stage-damage curves were used. Linear, square-root and polynomial stage-damage curves were applied for loss estimation as suggested by *Buck and Merkel* [1999] and *Büchele et al*. [2006] (Table 1). Stage-damage curves were calculated related to a) the water level above ground surface and b) the water level above basement floor if only the basement was affected and the water level above ground storey floor if also the ground floor was affected. For regressions between losses and the water level above ground surface (a), water levels below ground surface, i.e. if only the basement was affected, were set to zero. The calculation of stage-damage curves related to the water level within the building (b) was suggested by *Buck and Merkel* [1999]. Since groundwater flooding mainly affects basements, a better performance of the models following this approach is expected, since otherwise all losses where only the basement was affected are related to a water level of zero above ground surface.

Secondly, models taking into account the water level and the contamination as predicting factors were tested. That is, stage-damage curves were calculated separated for the three classes of contamination.

Finally, a model taking into account three or more loss determining factors, i.e. the structure of the micro-scale loss model FLEMOps [*Büchele et al.* 2006, Thieken et al., 2008] was applied. The FLEMOps model works in two stages, the basic model stage considers several water level classes, different residential building types and different building quality classes. An optional second model stage (FLEMOps+) allows the consideration of loss reducing or enhancing effects of private precautionary measures and contamination of the floodwater, respectively.

Models were judged suitable only if the results of both split sampling steps were similar and the errors in both validation runs acceptable [*Klemes*, 1986]. The performance of the loss models was evaluated by their mean bias error (MBE), mean absolute error (MAE) and root mean square error (RMSE) as well as with the ordinary bootstrap approach [*Efron*, 1979]. Confidence intervals for the mean loss ratios were calculated on the basis of 10000 simulated random samples of loss data which were drawn with replacement (bootstrap). The model performance was judged as sufficiently accurate, if the estimated mean loss ratios were within the 2.5%-97.5% confidence interval.

## 3. Results and discussion

### 3.1 Flood impact characteristics

All impact parameters, i.e. water level, flood duration, flow velocity indicator and contamination indicator, are significantly different for the groundwater flood in comparison with the riverine flood cases (Table 2). All parameters, except flood duration, were significantly lower even if only riverine flood cases with water levels up to 50 cm were analyzed. The low flood impact by high groundwater, except for the low average flood duration of less than 5 days, was expected due to the special characteristic of groundwater floods (see introduction). Generally, groundwater levels are decreasing relatively slowly. For instance, in Dresden above-average groundwater levels were still observed in 2003, although maximum levels were reached in August 2002 at most wells [*Landeshauptstadt Dresden*, 2005]. Particularly in areas more than 1 km away from a receiving stream, groundwater levels were decreasing very slowly [*Landeshauptstadt Dresden*, 2005]. The comparatively short flood durations reported in the interviews may be explained by effectively performed emergency measures: Maybe it was possible to seal the basements or pump the water out quickly, due to the low water levels.

The variability of impact parameters within the group of high groundwater cases is high with the smallest coefficient of variation of 82% for water level (Table 2). Due to this high data variability, groundwater cases are present in six of the seven impact clusters (Table 3).

However, most groundwater cases (55%) fall into the impact cluster four, which is characterized by low water levels, low flood duration, low flow velocity and low contamination (Table 3). No groundwater cases are present in cluster one which is characterized by high water levels, medium flood duration, high flow velocity and medium contamination.

### 3.2 Loss characteristics

The low flood impact expectedly leads to significantly lower flood losses for buildings and contents affected by high groundwater in contrast to buildings and contents affected by riverine floods (Figure 4). This is also true, if the losses caused by high groundwater are compared with the losses caused by riverine flooding up to 50 cm water level only. For the groundwater flood cases, average absolute building and contents losses were 14 456 Euro and 3 769 Euro, respectively, and loss ratios were 3% and 7%, respectively.

A correlation analysis reveals that all flood impact parameters are significantly correlated with the losses if all cases are taken into consideration (Table 4). Correlations with the building losses are slightly higher than those with the content losses. Water levels and losses show the highest correlation coefficients, confirming it to be the main loss influencing factor. More detailed information about impact and resistance factors influencing the losses in respect to this database were published by *Thieken et al*. [2005, 2007a]. The separation of interviews into high groundwater and riverine flood cases reduced the range of the impact parameters for each group (Table 2) and also the correlations between impact parameters and losses (Table 4). Within the group of high groundwater cases correlations are only significant between the losses and the water level as well as between the losses and the contamination indicator.

### 3.3 Modeling of losses due to high groundwater

3.3.1 Stage-damage curves

Regressions between losses and a) the water level above ground surface, and b) the water level above basement floor and above ground storey floor were calculated separately on basis of the two subsets of the surveyed data irrespective of groundwater or riverine flooding (Table 5). The mean building loss ratios were 2.44% with a 95% confidence interval from 1.63-3.43% for the first subset and 2.78% with a confidence interval from 1.71-4.03% for the second subset (Table 6). The mean contents loss ratios were 6.66% with a 95% confidence interval from 5.01-8.44% for the first subset and 7.54% with a confidence interval from 5.44-9.93% for the second subset. Assuming that only models whose estimates fall within the 95% confidence interval of the resampled loss ratios for both results of the split sampling are acceptable, the simulations reveal that stage-damage curves failed to estimate the loss ratios due to groundwater flooding with sufficient accuracy (Table 6). Most models overestimate the observed loss ratios, resulting in negative MBEs for all stage-damage curves except for the square-root function (sqrt) for building loss ratios in the first subset. Only that one was able to estimate the building loss ratios of the first subset well enough so that the mean was within the confidence interval. The calculation of stage-damage curves related to the water level above basement floor and above ground storey floor did not lead to the expected improvements of the model performance. Only the polynomial stage-damage curves related to the water level above basement floor and above ground storey floor succeeded in estimating the contents loss ratios of the second subset well. Since models should only be judged as suitable if both results of the split sampling are equally good, none of the stage-damage curves can be accepted for the estimation of losses caused by high groundwater.

3.3.2 Separate stage-damage curves for the three classes of contamination

Since losses due to groundwater flooding are not only correlated to the water level, but also to the contamination (Table 4), separate stage-damage curves were calculated for the three classes no, medium and high contamination (parameters not shown). That means that for each type of function, three parameter sets were derived. During the loss estimation, only the parameters set of the contamination class reported in the interview under study was applied. The consideration of the two impact factors water level and contamination in the loss models lead to some improvements of the estimation of losses due to groundwater flooding. Twice the building loss ratios of the first subset and once those of the second subset were estimated sufficiently accurate, i.e. the estimated mean loss ratios are within the 95% confidence interval of the resampled loss ratios (Table 6). Except for the linear stage-damage curve set, all stage-damage curve sets were able to estimate the contents loss ratios of the second subset sufficiently accurate (Table 6). However, still most estimations result in a negative MBE, revealing an overestimation of the loss ratios caused by groundwater flooding. No set of stage-damage curves was capable of performing equally well for both subsets, so that none of the models can be judged as suitable for the estimation of losses due to high groundwater.

### 3.3.3 The multifactorial model FLEMOps

It is expected, that the uncertainty in loss estimation is decreasing the more loss influencing factors are included in the loss models [*Merz et al.*, 2004; *Thieken et al.*, 2005; 2007b]. Therefore, the structure of the micro-scale multifactorial loss model FLEMOps [Thieken et al., 2008] was tested for the estimation of losses due to groundwater flooding as well. The parameters of the first and second stage of the FLEMOps-model were derived separately on basis of the two subsets (Figure 5 and Table 7). The first stage of the micro-scale FLEMOps model, which does not take into account the state of precaution and contamination, failed to estimate the building and contents loss ratios with sufficient accuracy (Table 6). The FLEMOps model also tends to overestimate the loss ratios due to groundwater flooding, resulting in mainly negative MBEs. However, FLEMOps+ was able to estimate the building loss ratios of both subsets and the contents loss ratios of the second subset with sufficient accuracy, i.e. the estimated mean loss ratios fall within the range that covers 95% of the resampled mean loss ratios. Therefore, FLEMOps+ is a suitable model for the estimation of building losses due to groundwater flooding. However, none of the loss models tested is suitable for the estimation of contents losses resulting from high groundwater levels. This might be due to the fact that groundwater floods are mainly affecting basements, which contents are commonly very different from contents in stories, regularly affected by riverine floods.

Most of the tested loss models were suitable to estimate building loss ratios due to riverine floods, but tend to overestimate losses due to groundwater flooding (Figure 6). The picture for contents losses is similar, although it seemed more difficult to sufficiently accurate estimate the contents loss ratios due to riverine floods of the second subset (data not shown). It has to be concluded that most loss models designed for riverine floods are as such not suitable to estimate losses due to high groundwater.

3.3.4 Loss models developed specifically for groundwater flooding

As shown above, new specific loss models have to be developed for groundwater flooding. One step in this direction is the development of stage-damage curves, separate stage-damage curves per class of contamination and the FLEMOps model just on basis of loss data from groundwater flooding cases (parameters not shown). The application of the models reveals significant improvements of the model performances. Both square-root stage-damage curves and both stages of the micro-scale FLEMOps model, derived from the groundwater flood loss data only, were able to estimate the building loss ratios of both subsets sufficiently accurate (Table 8).All tested loss models originated from groundwater flood loss data only, were capable of estimating the contents loss ratios of both subsets sufficiently well. The best performance was found for FLEMOps+ with nearly no bias: the MBEs for building loss ratios were 0% and 0.03% and for the content loss ratios -0.05% and 0.04%. Also the MAEs with about 0.2% for building and about 0.4% for the contents loss ratios and RMSEs with 1.2% and 1.6% for building and 2.1% and 2.5% for contents loss ratios were the lowest in comparison with the estimations of the other models (Table 8). Concerning the building loss ratios, the FLEMOps+ developed on basis of groundwater flood loss data only, delivered better estimates than the FLEMOps+ developed with all loss data, especially with a lower bias (Tables 6 and 8). Thus, models considering more loss influencing factors besides the water level and particularly loss models developed specifically on the basis of groundwater flood data only, should be used for estimations of losses due to high groundwater flooding.

## 4. Conclusions

Inundations due to high groundwater show significantly different impact characteristics than riverine floods. In an empirical data set from the August 2002 flood in Germany, the parameters water level, flood duration, flow velocity indicator and contamination indicator were all significantly lower than the ones of the riverine flood. Thus, groundwater floods resulted in significantly lower losses to residential buildings and contents than riverine floods. Losses due to high groundwater were significantly correlated with the water level and the contamination indicator. However, stage-damage curves taking into account the water level and the contamination class were still not able to estimate losses due to groundwater floods with sufficient accuracy. From the tested models, which were derived using all available loss data, only the micro-scale multifactorial model FLEMOps+ was able to estimate building loss ratios due to high groundwater sufficiently accurate. Therefore, new loss models have to be developed specifically for groundwater flooding. One step in this direction is the development of loss models just on basis of loss data from groundwater flooding. From all such models tested, again FLEMOps+ performed best, confirming that the uncertainty in loss estimation can be reduced if more predictive variables, besides the water level, are taken into consideration. A prerequisite of this approach is the continuous collection of more and particularly more detailed flood loss data. Additionally, further research is necessary to investigate the main factors influencing the losses due to groundwater flooding and to develop specific models for their assessment.

**Acknowledgements**

The analysis was undertaken within the Project MULTISURE - Development of Multisequential Mitigation Strategies for Urban Areas with Risk of Groundwater Flood. The telephone interviews were undertaken within the German Research Network Natural Disasters (DFNK) in cooperation between the Section Engineering Hydrology at the GFZ Potsdam and the Deutsche Rückversicherung AG. We thank the Deutsche Rückversicherung AG and the German Ministry for Education and Research (BMBF) (no. 01SFR9969/5) for the financial support.

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Table 1 Formulas of stage-damage curves for loss estimation

| Stage-damage curves related to the water levels above ground surface | | |
|---|---|---|
| Description | Formula for | |
| | building loss | contents loss |
| Linear (lin) | $L_B = a_B+b_B*h$ | $L_C = a_C+b_C*h$ |
| Square-root (sqrt) | $L_B = a_B+b_B*sqrt(h)$ | $L_C = a_C+b_C*sqrt(h)$ |
| Polynomial (poly) | $L_B = a_B+b_B*h+c_B*h^2$ | $L_C = a_C+b_C*h+c_C*h^2$ |
| Stage-damage curves related to the water level above basement floor if only the basement is affected or the water level above ground storey floor if also stories are affected | | |
| Linear (lin-ug) | basement affected: $L_B = a_{Bu}+b_{Bu}*h_u$<br>stories affected: $L_B = a_{Bg}+b_{Bg}*h_g$ | basement affected: $L_C = a_{Cu}+b_{Cu}*h_u$<br>stories affected: $L_C = a_{Cg}+b_{Cg}*h_g$ |
| Square-root (sqrt-ug) | basement affected: $L_B = a_{Bu}+b_{Bu}*sqrt(h_u)$<br>stories affected: $L_B = a_{Bg}+b_{Bg}*sqrt(h_g)$ | basement affected: $L_C = a_{Cu}+b_{Cu}*sqrt(h_u)$<br>stories affected: $L_C = a_{Cg}+b_{Cg}*sqrt(h_g)$ |
| Polynomial (poly-ug) | basement affected: $L_B = a_{Bu}+b_{Bu}*h_u+c_{Bu}*h_u^2$<br>stories affected: $L_B = a_{Bg}+b_{Bg}*h_g+c_{Bg}*h_g^2$ | basement affected: $L_C = a_{Cu}+b_{Cu}*h_u+c_{Cu}*h_u^2$<br>stories affected: $L_C = a_{Cg}+b_{Cg}*h_g+c_{Cg}*h_g^2$ |

$L_B$: building loss ratio

$L_C$: contents loss ratio

$h$: water level above ground surface [cm]

$h_u$: water level above basement floor [cm]

$h_g$: water level above ground storey floor [cm]

a, b, c: parameters (subscript letters indicate to which case they are related)

Table 2 Descriptive statistics (number of cases (n), 25%-, 75%-percentile, median, mean, coefficient of variation) of the flood impact parameters: water level, flood duration, flow velocity indicator and contamination indicator

| High groundwater | | | | |
|---|---|---|---|---|
| | water level* [cm] | duration [h] | flow velocity (indicator) | contamination (indicator) |
| number of cases (n) | 257 | 258 | 264 | 263 |
| 25%-percentile | -170 | 12 | stagnant | no |
| median | -108 | 48 | moderate | no |
| mean | -102 | 116 | 0.8 | 0.3 |
| 75%-percentile | -32 | 120 | moderate | medium |
| coefficient of variation [%] | 82 | 180 | 104 | 175 |
| Riverine flood (all) | | | | |
| | water level* [cm] | duration [h] | flow velocity (indicator) | contamination (indicator) |
| number of cases (n) | 1415 | 1399 | 1403 | 1408 |
| 25%-percentile | 20 | 24 | moderate | no |
| median | 95 | 72 | moderate | medium |
| mean | 94 | 148 | 1.5 | 0.7 |
| 75%-percentile | 172 | 168 | high | medium |
| coefficient of variation [%] | 154 | 138 | 39 | 93 |
| Riverine flood (water level ≤ 50cm) | | | | |
| | water level* [cm] | duration [h] | flow velocity (indicator) | contamination (indicator) |
| number of cases (n) | 513 | 503 | 503 | 504 |
| 25%-percentile | -109 | 12 | moderate | no |
| median | -20 | 48 | moderate | no |
| mean | -46 | 95 | 1.4 | 1.0 |
| 75%-percentile | 28 | 96 | high | high |
| coefficient of variation [%] | 182 | 168 | 38 | 113 |

* negative values indicate a water level below ground surface, affecting only the basement

Table 3: Mean values of flood impact variables in seven clusters and the total data set as well as the number and fraction of cases affected by high groundwater within each cluster

| Cluster | Water level [cm] | Flood duration [h] | Flow velocity (indicator) | Contamination (indicator) | Groundwater cases n | Groundwater cases [%] |
|---|---|---|---|---|---|---|
| 1 | 306 | 89 | 2.0 | 0.7 | 0 | 0 |
| 2 | -28 | 54 | 2.0 | 0.2 | 46 | 17 |
| 3 | 99 | 92 | 1.0 | 0.2 | 23 | 9 |
| 4 | -124 | 59 | 0.6 | 0.2 | 146 | 55 |
| 5 | 93 | 590 | 1.3 | 0.9 | 17 | 6 |
| 6 | 119 | 141 | 1.0 | 1.3 | 9 | 3 |
| 7 | 105 | 71 | 2.1 | 1.4 | 11 | 4 |
| Total | 64 | 143 | 1.4 | 0.7 | 252* | 95* |

* 12 groundwater cases (5%) could not be assigned to a cluster due to a lack of information

Table 4 Correlations between impact factors and resulting losses for all cases and divided for the two flood types: Sperman-Rho (pair-wise data exclusion; * correlation is significant)

| All data | | | | |
|---|---|---|---|---|
| | water level [cm] | duration [h] | flow velocity (indicator) | contamination (indicator) |
| absolute building losses [€] | 0.66* | 0.40* | 0.20* | 0.43* |
| absolute contents losses [€] | 0.50* | 0.25* | 0.06* | 0.28* |
| building loss ratios | 0.67* | 0.43* | 0.18* | 0.42* |
| contents loss ratios | 0.54* | 0.30* | 0.07* | 0.29* |
| High groundwater | | | | |
| | water level [cm] | duration [h] | flow velocity (indicator) | contamination (indicator) |
| absolute building losses [€] | 0.41* | 0.13 | 0.09 | 0.22* |
| absolute contents losses [€] | 0.31* | 0.07 | 0.06 | 0.23* |
| building loss ratios | 0.35* | 0.11 | 0.03 | 0.19* |
| contents loss ratios | 0.38* | 0.14 | 0.04 | 0.25* |
| Riverine flood (all) | | | | |
| | water level [cm] | duration [h] | flow velocity (indicator) | contamination (indicator) |
| absolute building losses [€] | 0.59* | 0.42* | 0.10* | 0.38* |
| absolute contents losses [€] | 0.42* | 0.24* | -0.04 | 0.23* |
| building loss ratios | 0.60* | 0.46* | 0.05 | 0.37* |
| contents loss ratios | 0.46* | 0.29* | -0.02 | 0.24* |

Table 5 Parameters of the stage-damage curves calculated on basis of both subsets (for more detailed description and formulas see Table 1)

| | Parameters calculated on basis of the | | | |
|---|---|---|---|---|
| Description | 1st subset | 2nd subset | 1st subset | 2nd subset |
| | building loss | | contents loss | |
| lin | $a_B=0.069499$<br>$b_B=5.5359*10^{-4}$ | $a_B=0.051685$<br>$b_B=7.2473*10^{-4}$ | $a_C=0.16961$<br>$b_C=9.407*10^{-4}$ | $a_C=0.17031$<br>$b_C=1.1743*10^{-4}$ |
| sqrt | $a_B=3.7455*10^{-2}$<br>$b_B=1.1534*10^{-2}$ | $a_B=2.0646*10^{-2}$<br>$b_B=1.3109*10^{-2}$ | $a_C=9.043*10^{-2}$<br>$b_C=2.1918*10^{-2}$ | $a_C=9.3816*10^{-2}$<br>$b_C=2.3717*10^{-2}$ |
| poly | $a_B=4.3603*10^{-2}$<br>$b_B=1.2029*10^{-3}$<br>$c_B=-1.6393*10^{-6}$ | $a_B=3.4853*10^{-2}$<br>$b_B=1.1765*10^{-3}$<br>$c_B=-1.2728*10^{-6}$ | $a_C=9.1112*10^{-2}$<br>$b_C=2.6244*10^{-3}$<br>$c_C=-3.925*10^{-6}$ | $a_C=11.152*10^{-2}$<br>$b_C=2.5018*10^{-3}$<br>$c_C=-3.7584*10^{-6}$ |
| lin-ug | $a_{Bu}=0.0099322$<br>$b_{Bu}=3.9305*10^{-4}$<br>$a_{Bg}=0.15469$<br>$b_{Bg}=3.4861*10^{-4}$ | $a_{Bu}=0.016133$<br>$b_{Bu}=3.0054*10^{-4}$<br>$a_{Bg}=0.14137$<br>$b_{Bg}=4.1598*10^{-4}$ | $a_{Cu}=0.039269$<br>$b_{Cu}=6.1977*10^{-4}$<br>$a_{Cg}=0.36703$<br>$b_{Cg}=3.9926*10^{-4}$ | $a_{Cu}=0.054412$<br>$b_{Cu}=6.2799*10^{-4}$<br>$a_{Cg}=0.38502$<br>$b_{Cg}=4.0615*10^{-4}$ |
| sqrt-ug | $a_{Bu}=-1.5178*10^{-2}$<br>$b_{Bu}=0.72451*10^{-2}$<br>$a_{Bg}=11.506*10^{-2}$<br>$b_{Bg}=0.8229*10^{-2}$ | $a_{Bu}=-0.30922*10^{-2}$<br>$b_{Bu}=0.55402*10^{-2}$<br>$a_{Bg}=9.5946*10^{-2}$<br>$b_{Bg}=0.97741*10^{-2}$ | $a_{Cu}=-0.82001*10^{-2}$<br>$b_{Cu}=1.2022*10^{-2}$<br>$a_{Cg}=29.529*10^{-2}$<br>$b_{Cg}=1.2242*10^{-2}$ | $a_{Cu}=0.2265*10^{-2}$<br>$b_{Cu}=1.2654*10^{-2}$<br>$a_{Cg}=32.329*10^{-2}$<br>$b_{Cg}=1.1326*10^{-2}$ |
| poly-ug | $a_{Bu}=-0.02179*10^{-2}$<br>$b_{Bu}=0.74216*10^{-3}$<br>$c_{Bu}=-1.4728*10^{-6}$<br>$a_{Bg}=13.743*10^{-2}$<br>$b_{Bg}=0.67444*10^{-3}$<br>$c_{Bg}=-0.86268*10^{-6}$ | $a_{Bu}=0.88989*10^{-2}$<br>$b_{Bu}=0.5325*10^{-3}$<br>$c_{Bu}=-0.95487*10^{-6}$<br>$a_{Bg}=11.151*10^{-2}$<br>$b_{Bg}=1.0744*10^{-3}$<br>$c_{Bg}=-1.9105*10^{-6}$ | $a_{Cu}=3.8029*10^{-2}$<br>$b_{Cu}=0.65048*10^{-3}$<br>$c_{Cu}=-0.11799*10^{-6}$<br>$a_{Cg}=29.305*10^{-2}$<br>$b_{Cg}=1.7861*10^{-3}$<br>$c_{Cg}=-3.5403*10^{-6}$ | $a_{Cu}=2.3413*10^{-2}$<br>$b_{Cu}=1.403*10^{-3}$<br>$c_{Cu}=-2.9239*10^{-6}$<br>$a_{Cg}=33.318*10^{-2}$<br>$b_{Cg}=1.5988*10^{-3}$<br>$c_{Cg}=-4.0261*10^{-6}$ |

Table 6 Surveyed and estimated mean loss ratios of losses to buildings and contents caused by groundwater flooding

| Survey (bootstrap) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Building loss | | | | | Contents loss | | | | |
| | mean [%] | 2.5-percentile [%] | | 97.5-percentile [%] | | mean [%] | 2.5-percentile [%] | | 97.5-percentile [%] | |
| 1st subset | 2.44 | 1.63 | | 3.42 | | 6.65 | 5.01 | | 8.44 | |
| 2nd subset | 2.78 | 1.71 | | 4.03 | | 7.54 | 5.44 | | 9.93 | |
| Estimations with stage-damage curves | | | | | | | | | | |
| | mean [%] | in cf. i.[#] | MBE [%] | MAE [%] | RMSE [%] | mean [%] | in cf. i. | MBE [%] | MAE [%] | RMSE [%] |
| lin - 1st ss* | 5.46 | no | -0.21 | 0.31 | 1.27 | 17.50 | no | -0.92 | 1.01 | 3.82 |
| lin - 2nd ss | 7.15 | no | -0.39 | 0.55 | 2.03 | 17.30 | no | -0.85 | 1.13 | 4.09 |
| sqrt - 1st ss | 3.10 | yes | 0.02 | 0.16 | 0.95 | 11.26 | no | -0.47 | 0.67 | 2.73 |
| sqrt - 2nd ss | 4.51 | no | -0.18 | 0.38 | 1.75 | 10.49 | no | -0.26 | 0.72 | 3.12 |
| poly - 1st ss | 3.94 | no | -0.08 | 0.22 | 1.05 | 12.11 | no | -0.50 | 0.70 | 2.71 |
| poly - 2nd ss | 4.77 | no | -0.19 | 0.39 | 1.69 | 10.00 | no | -0.22 | 0.70 | 3.03 |
| lin-ug - 1st ss | 4.11 | no | -0.09 | 0.19 | 0.93 | 10.84 | no | -0.43 | 0.64 | 2.87 |
| lin-ug - 2nd ss | 4.67 | no | -0.16 | 0.37 | 1.97 | 10.38 | no | -0.17 | 0.68 | 3.26 |
| sqrt-ug - 1st ss | 4.13 | no | -0.09 | 0.19 | 0.95 | 10.50 | no | -0.43 | 0.63 | 2.85 |
| sqrt-ug - 2nd ss | 4.67 | no | -0.15 | 0.35 | 1.86 | 10.02 | no | -0.16 | 0.68 | 3.19 |
| poly-ug - 1st ss | 3.89 | no | -0.08 | 0.21 | 1.16 | 9.81 | no | -0.34 | 0.59 | 2.58 |
| poly-ug - 2nd ss | 4.17 | no | -0.07 | 0.30 | 1.59 | 8.77 | yes | -0.11 | 0.61 | 2.95 |
| Estimations with stage-damage curves calculated separately for the three classes of contamination | | | | | | | | | | |
| lin - 1st ss | 4.48 | no | -0.12 | 0.26 | 1.27 | 13.73 | no | -0.64 | 0.81 | 3.20 |
| lin - 2nd ss | 6.29 | no | -0.30 | 0.48 | 1.90 | 15.51 | no | -0.76 | 1.06 | 3.91 |
| sqrt - 1st ss | 3.13 | yes | 0.01 | 0.17 | 1.00 | 10.04 | no | -0.38 | 0.61 | 2.60 |
| sqrt - 2nd ss | 4.15 | no | -0.14 | 0.35 | 1.72 | 9.87 | yes | -0.23 | 0.69 | 3.08 |
| poly - 1st ss | 3.29 | yes | -0.02 | 0.20 | 1.12 | 10.59 | no | -0.40 | 0.63 | 2.57 |
| poly - 2nd ss | 4.35 | no | -0.15 | 0.36 | 1.68 | 9.25 | yes | -0.17 | 0.66 | 2.98 |
| lin-ug - 1st ss | 3.79 | no | -0.06 | 0.19 | 1.04 | 9.89 | no | -0.34 | 0.60 | 2.89 |
| lin-ug - 2nd ss | 4.16 | no | -0.11 | 0.33 | 1.79 | 9.77 | yes | -0.16 | 0.65 | 3.15 |
| sqrt-ug - 1st ss | 3.75 | no | -0.05 | 0.19 | 1.03 | 9.67 | no | -0.33 | 0.58 | 2.81 |
| sqrt-ug - 2nd ss | 4.04 | yes | -0.09 | 0.30 | 1.65 | 9.52 | yes | -0.14 | 0.65 | 3.11 |
| poly-ug - 1st ss | 3.74 | no | -0.05 | 0.18 | 1.08 | 9.62 | no | -0.34 | 0.60 | 2.90 |
| poly-ug - 2nd ss | 4.11 | no | -0.09 | 0.32 | 1.66 | 9.61 | yes | -0.15 | 0.63 | 3.03 |
| Estimations with the loss model FLEMOps | | | | | | | | | | |
| FLEMOps - 1st ss | 3.70 | no | -0.07 | 0.21 | 1.09 | 12.54 | no | -0.36 | 0.51 | 2.36 |
| FLEMOps - 2nd ss | 4.52 | no | -0.17 | 0.38 | 1.75 | 12.99 | no | -0.33 | 0.61 | 2.93 |
| FLEMOps+ - 1st ss | 2.47 | yes | 0.01 | 0.18 | 1.13 | 9.40 | no | -0.19 | 0.40 | 2.09 |
| FLEMOps+ - 2nd ss | 3.30 | yes | -0.07 | 0.31 | 1.60 | 9.80 | yes | -0.16 | 0.48 | 2.52 |

[#] in cf. i.: within 95% confidence interval

* ss: subset

Table 7: Factors for the second stage of the micro-scale FLEMOps model (FLEMOps+): Scaling factors for losses of residential buildings and household contents due to private precautionary measures and contamination calculated on basis of the two subsets of loss data.

| | Scaling factors building loss | | Scaling factors content loss | |
|---|---|---|---|---|
| | 1st subset | 2nd subset | 1st subset | 2nd subset |
| No contamination, no precaution | 0.71 | 0.57 | 0.79 | 0.69 |
| No contamination, good precaution | 0.48 | 0.46 | 0.56 | 0.69 |
| No contamination, very good precaution | 0.16 | 0.29 | 0.25 | 0.36 |
| Medium contamination, no precaution | 1.40 | 1.31 | 1.20 | 1.19 |
| Medium contamination, good precaution | 0.93 | 1.06 | 0.85 | 1.19 |
| Medium contamination, very good precaution | 0.32 | 0.67 | 0.38 | 0.62 |
| High contamination, no precaution | 1.93 | 2.00 | 1.64 | 1.51 |
| High contamination, good precaution | 1.29 | 1.61 | 1.16 | 1.51 |
| High contamination, very good precaution | 0.44 | 1.02 | 0.52 | 0.79 |

Table 8 Surveyed and estimated mean loss ratios of losses to buildings and contents caused by groundwater flooding. All models were developed on the basis of groundwater flood loss data only.

| Survey (bootstrap) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Building loss | | | | | Contents loss | | | | |
| | mean [%] | 2.5-percentile [%] | | 97.5-percentile [%] | | mean [%] | 2.5-percentile [%] | | 97.5-percentile [%] | |
| $1^{st}$ subset | 2.44 | 1.63 | | 3.42 | | 6.65 | 5.01 | | 8.44 | |
| $2^{nd}$ subset | 2.78 | 1.71 | | 4.03 | | 7.54 | 5.44 | | 9.93 | |
| Estimations with stage-damage curves | | | | | | | | | | |
| | mean [%] | in cf. i.$^{\#}$ | MBE [%] | MAE [%] | RMSE [%] | mean [%] | in cf. i. | MBE [%] | MAE [%] | RMSE [%] |
| lin - $1^{st}$ ss* | 2.75 | yes | -0.01 | 0.18 | 1.03 | 7.56 | yes | -0.10 | 0.47 | 2.09 |
| lin - $2^{nd}$ ss | 5.30 | no | -0.32 | 0.56 | 3.65 | 6.22 | yes | 0.11 | 0.54 | 2.92 |
| sqrt - $1^{st}$ ss | 2.77 | yes | -0.01 | 0.18 | 1.03 | 7.64 | yes | -0.12 | 0.47 | 2.06 |
| sqrt - $2^{nd}$ ss | 3.93 | yes | -0.16 | 0.40 | 2.25 | 6.01 | yes | 0.13 | 0.53 | 2.93 |
| poly - $1^{st}$ ss | 2.72 | yes | -0.01 | 0.18 | 1.05 | 7.63 | yes | -0.11 | 0.47 | 2.08 |
| poly - $2^{nd}$ ss | 19.94 | no | -1.96 | 2.20 | 23.04 | 5.79 | yes | 0.16 | 0.53 | 2.98 |
| Estimations with stage-damage curves calculated separately for the three classes of contamination | | | | | | | | | | |
| lin - $1^{st}$ ss | 2.65 | yes | 0.00 | 0.17 | 1.05 | 7.02 | yes | -0.08 | 0.42 | 1.99 |
| lin - $2^{nd}$ ss | 4.49 | no | -0.25 | 0.49 | 3.13 | 6.22 | yes | 0.09 | 0.53 | 2.89 |
| sqrt - $1^{st}$ ss | 2.66 | yes | 0.00 | 0.17 | 1.04 | 7.07 | yes | -0.09 | 0.42 | 1.97 |
| sqrt - $2^{nd}$ ss | 3.44 | yes | -0.12 | 0.37 | 2.11 | 6.01 | yes | 0.11 | 0.52 | 2.91 |
| poly - $1^{st}$ ss | 2.63 | yes | 0.00 | 0.18 | 1.07 | 7.02 | yes | -0.08 | 0.42 | 1.99 |
| poly - $2^{nd}$ ss | - | - | - | - | - | 5.87 | yes | 0.13 | 0.53 | 2.95 |
| Estimations with the loss model FLEMOps | | | | | | | | | | |
| FLEMOps - $1^{st}$ ss | 2.65 | yes | -0.02 | 0.20 | 1.18 | 7.35 | yes | -0.08 | 0.42 | 2.15 |
| FLEMOps - $2^{nd}$ ss | 2.41 | yes | 0.03 | 0.24 | 1.55 | 7.09 | yes | 0.03 | 0.41 | 2.55 |
| FLEMOps+ - $1^{st}$ ss | 2.43 | yes | 0.00 | 0.20 | 1.20 | 6.55 | yes | -0.05 | 0.40 | 2.14 |
| FLEMOps+ - $2^{nd}$ ss | 2.19 | yes | 0.03 | 0.25 | 1.57 | 6.66 | yes | 0.04 | 0.38 | 2.45 |

$^{\#}$ in cf. i.: within confidence interval

* ss: subset

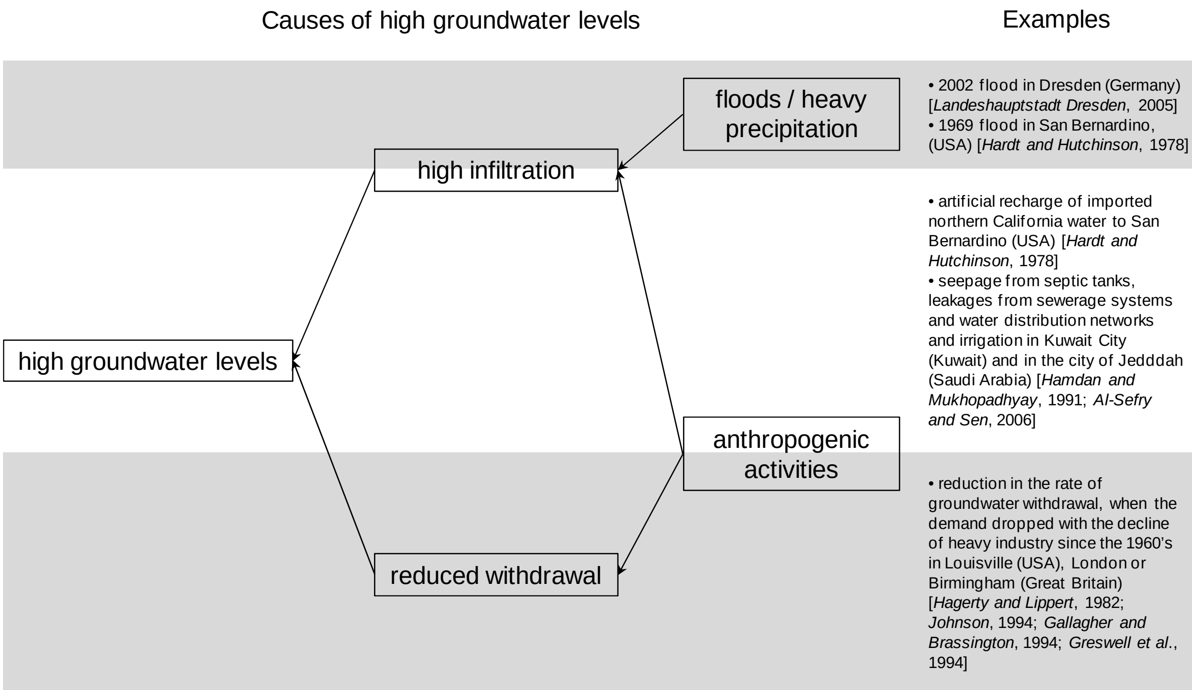


Figure 1 Overview and examples of different causes for high groundwater levels

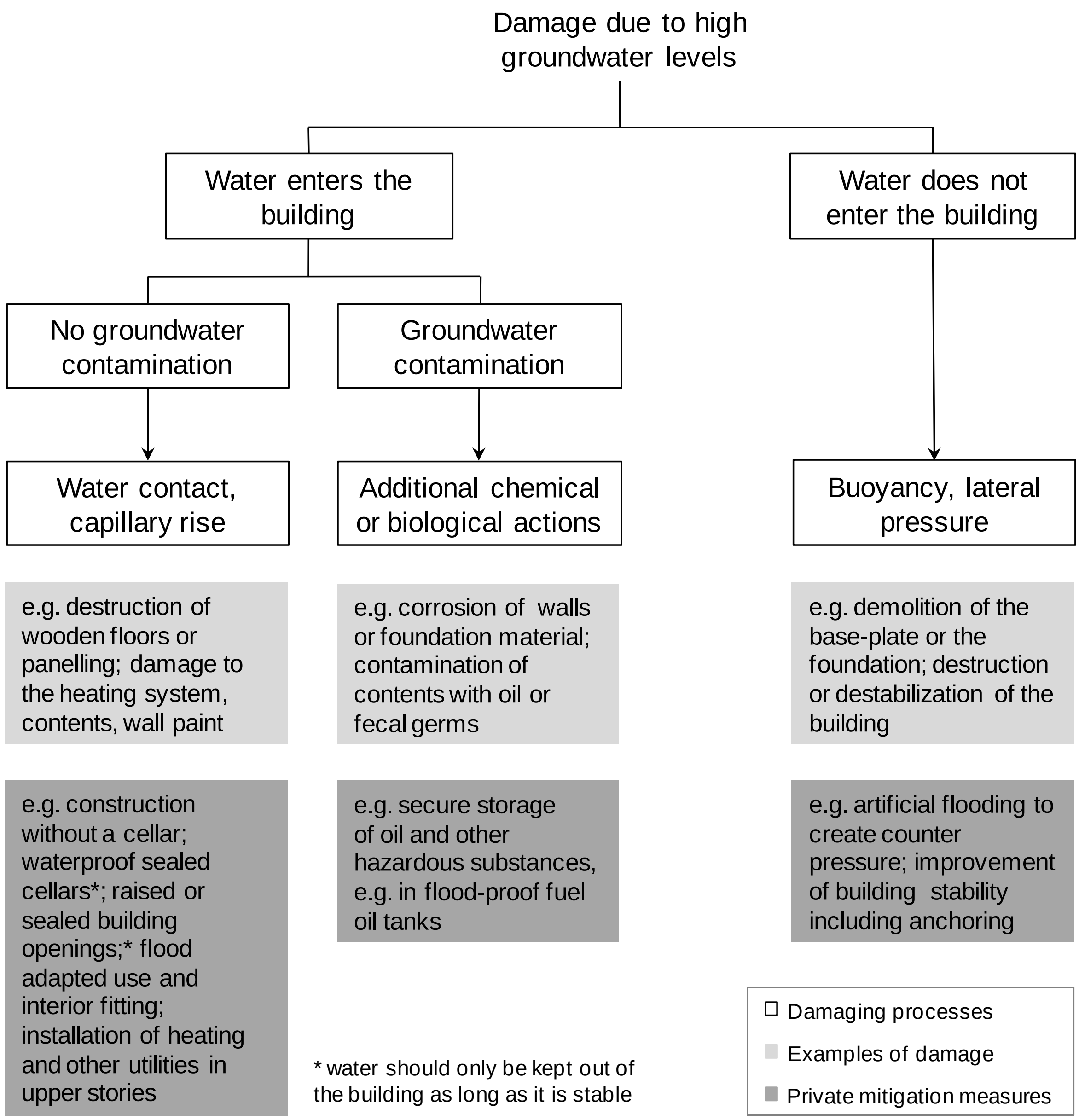


Figure 2 Overview of damage due to high groundwater levels and possible private mitigation measures

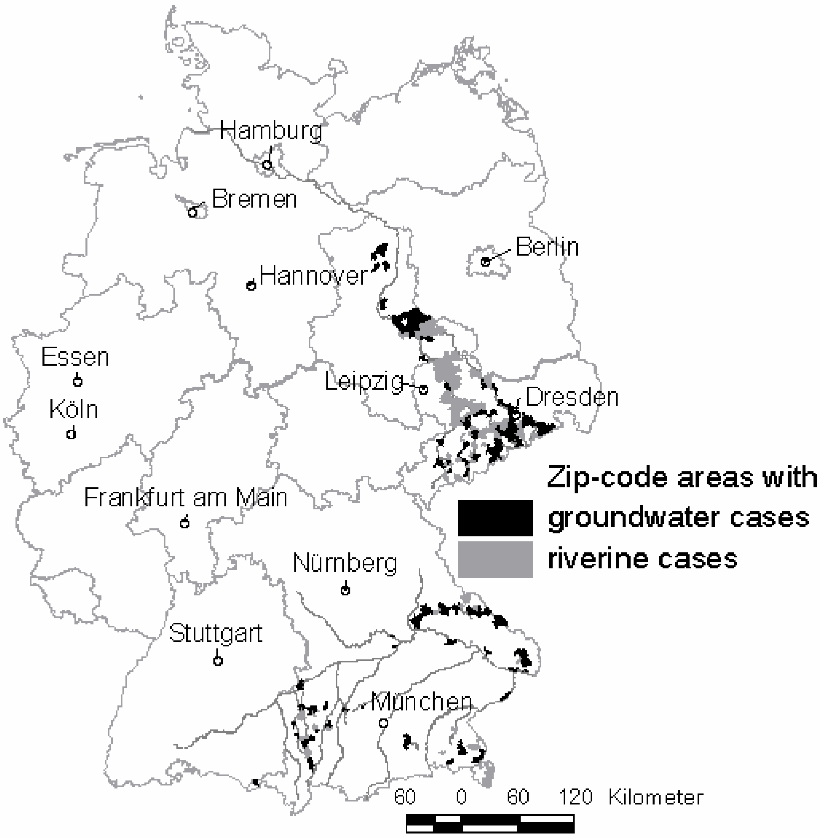


Figure 3 Study area in the Elbe and Danube catchments in Germany. Marked are the Zip-code areas where interviews were undertaken.

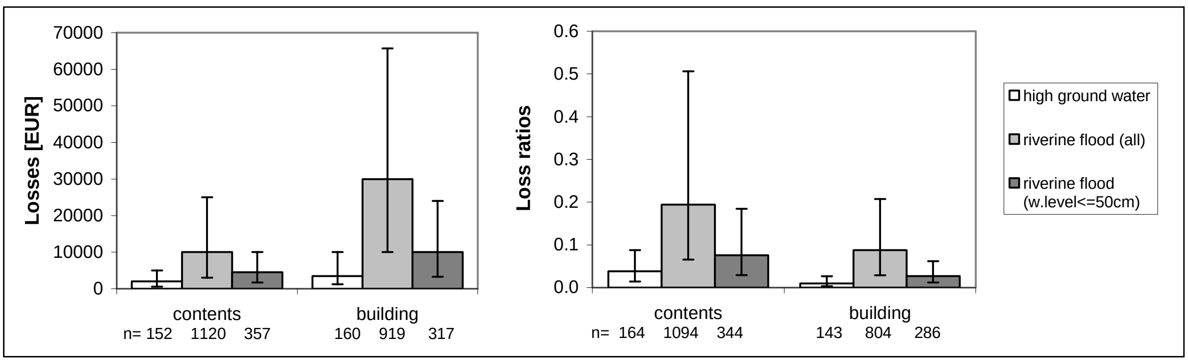


Figure 4 Absolute losses and loss ratios of buildings and contents separated for the high groundwater cases, all riverine flood cases and riverine flood cases with water levels up to 50 cm only (median, 25%-, 75%-percentiles).

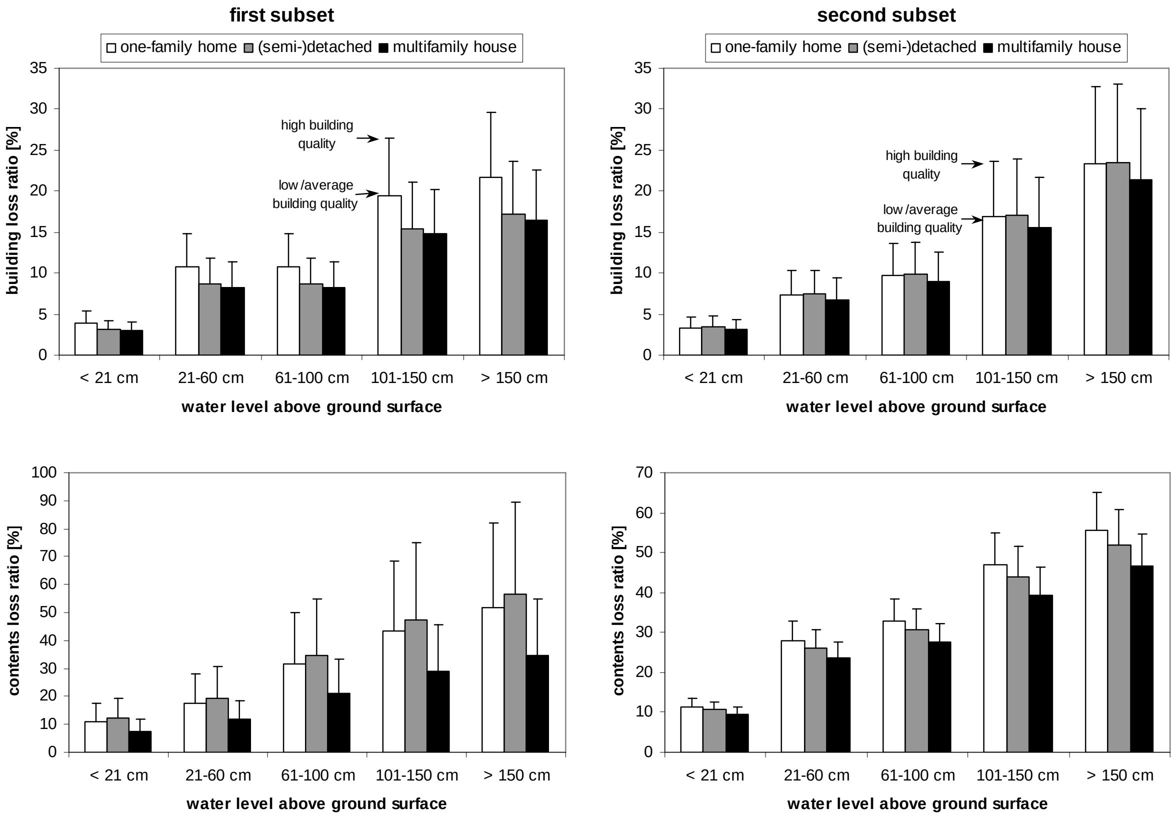


Figure 5 First stage of the micro-scale FLEMOps model: estimates of flood losses to residential buildings and contents considering water level, building type and building quality; derived from both subsets of loss data.

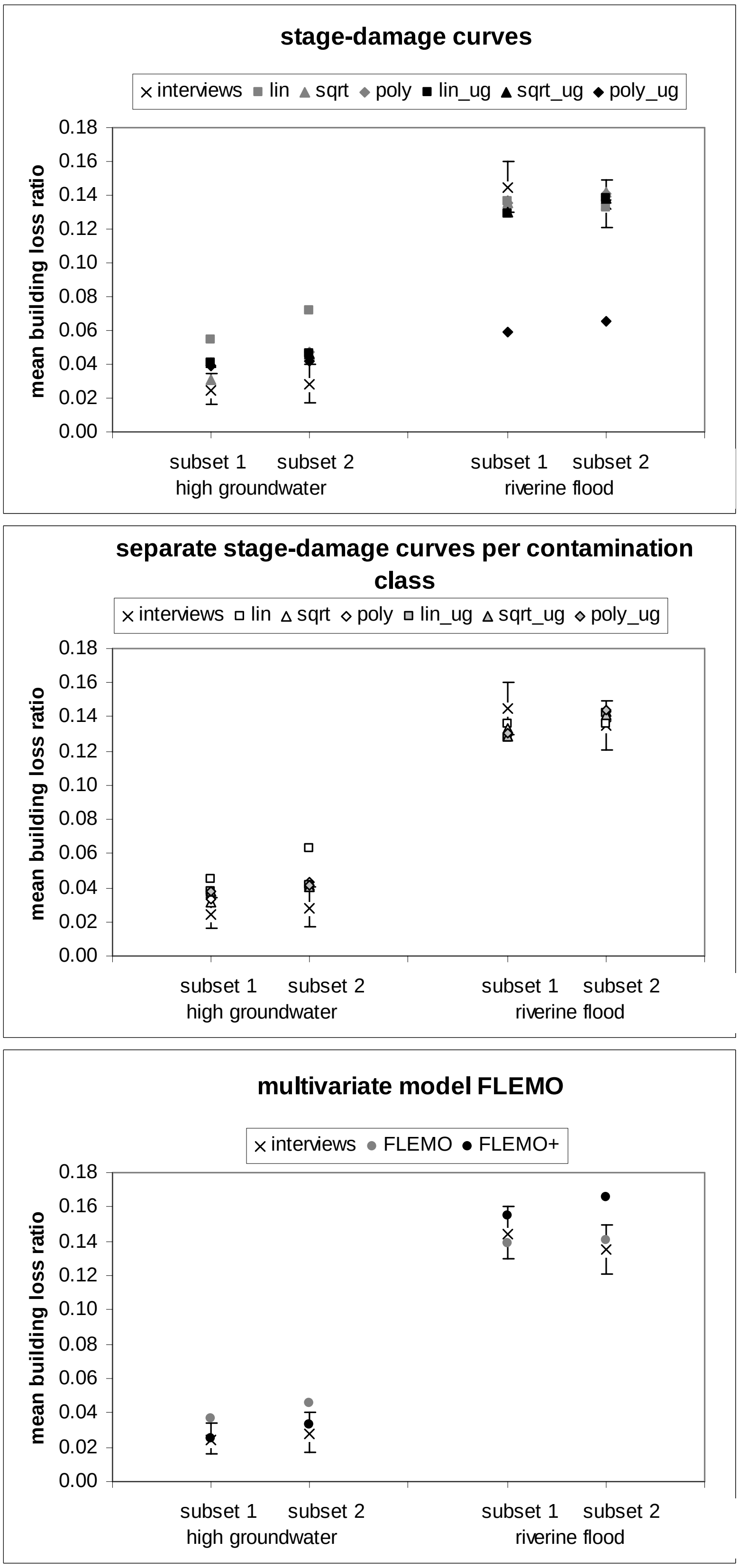


Figure 6 Surveyed and estimated mean ratios of losses to buildings caused by groundwater flooding and riverine flooding. For the surveyed data the mean and the 2.5% to 97.5% confidence intervals, calculated by bootstrap, are shown.