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Estimation of an absolute flood damage curve based on an Austrian case study under a dam breach scenario

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Abstract. To date, in Austria no empirical assessment of absolute damage curves has been realized on the basis of detailed information on flooded buildings due to a dam breach, presumably because of the lack of data. This paper tries to fill this gap by estimating an absolute flood-damage curve, based on data of a recent flood event in Austria in 2006. First, a concise analysis of the case study area is conducted, i.e., the maximum damage potential is identified by using raster-based GIS. Thereafter, previous literature findings on existing flood-damage functions are considered in order to determine a volume-water damage function that can be used for further flood damage assessment. Finally, the flood damage function is cross validated and applied in prediction of damage potential in the study area. For future development of the estimated flood damage curve, and to aid more general use, we propose verification against field data on damage caused by natural waves in rivers.

1 Introduction

Damage functions represent a fundamental concept in the assessment of flood damage, indicating, e.g., the building damage due to inundation (e.g., Merz et al., 2004). As supported by Merz et al. (2004, p. 154) "[...] depth-damage functions are seen as the essential building blocks upon which flood damage assessments are based; and they are internationally accepted as the standard approach to assessing urban flood damage (Smith, 1994)" (see also Büchele et al., 2006). In the derivation of flood damage curves, historical data have to be continuously actualized, whereby a regional extension of the availability of flood damage data/curves is considered to be fruitful (e.g., Jak and Kok, 2000). To the authors' knowledge, no empirical flood-damage curves estimated on the basis of actual data on damage, water depths and square metres of flooded usable surfaces, collected in the aftermath of a flood event, are to date available in Austria. With reference to the flood event in Austria in 2002, actual damage functions were adapted for Austria, explaining the absolute damage for several buildings in terms of water depth based on the commonly used German database "HOWAS (Hochwasserschadensdatenbank) of the Bayerisches Landesamt für Wasserwirtschaft" (see e.g., Lebensministerium, 2004). Merz et al. (2004, p. 156) showed that water depth explains some of the variability in flood damage, but that other parameters, such as the economic sector to which commercial buildings belong, building use, etc., have to be considered as well. The main aim of this paper is to provide a flood damage function using newly collected data. This function is then compared to other available flood damage curves. In other words, our purpose is to follow Jak and Kok (2000) and to enrich the functions based on international literature and databases by using accurate regional data. Additionally, a further purpose is to include a very specific kind of damage i.e. oil damage, often observed in praxis, but rarely explicitly modelled in damage functions. Müller (2000) found that during floods in Germany, heating oil tanks have a great impact on the magnitude of damage on residential buildings. Similarly, Kreibich (2005) showed that although in flooded areas surveyed, only 15% of the private central heating systems were based on oil, 44% of the households claimed contamination of buildings and contents by oil or petrol, implying relatively large externality effects. Thieken et al. (2005, p. 15) analyzed flood damage in private households and noted several influencing factors on the basis of damage data gathered in the aftermath of a severe flood event. They found that "the effect of floodwater contamination especially by oil, petrol or hazardous waste, should gain more attention." Therefore, in contrast to most of the recent literature on flood-damage curves, in this paper, the

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flood-damage curve is estimated with reference to two main types of residential damage: (1) "regular" damage and (2) oil damage (also including some similar static damage).

When using the term "damage", a clear definition of what is meant in a particular context has to be given, since the term's meaning is very general in everyday language, but also quite a far reaching concept in several theoretical approaches[1]. Following Kates (1965), several classifications of flood damage have been used in the past, whereby most studies distinguish between tangible and intangible damage. In contrast to tangible damage, intangible damage cannot be quantified in monetary terms. We therefore concentrate on tangible damage here, which is usually further divided into direct and indirect damage (see, e.g., Penning-Rowsell and Chatterton, 1977; Green et al., 1983; Smith, 1994; Parker, 2000; Dutta et al., 2003, 2006).

Direct damage to assets is caused by direct contact of floodwater (e.g., Lekuthai and Vongvisessomjai, 2001; Dutta et al., 2003; Merz et al., 2004). In contrast, indirect damage is induced by the consequences of physical contact of the property with floodwater (Parker, 2000). Büchele et al. (2006) specify indirect damage as that which occurs – with respect to space or time – outside the direct flood event. Typically, indirect primary damage will consist of, e.g., business interruption, disruptions of traffic, trade and public services (Merz et al., 2004), whereas the impact on the regional and national economy can be seen as an example of indirect secondary damage (Dutta et al., 2003). Gissing and Blong (2004) belong to the few authors who studied damage to businesses, including business interruption. They found little direct relationship between commercial damage and overfloor water depth. In general, flood damage functions are not necessarily instructive in (direct and indirect) damage estimation, especially relating to commercial buildings. We therefore focus on residential buildings only. Direct damage is sometimes also further subdivided into primary and secondary damage. Direct primary damage, for example, typically includes damage to buildings, contents, infrastructure, crops and animals. If a flood causes fire damage, contaminates land and reduces crop yields (Parker, 2000) or necessitates land and environmental recovery (Dutta et al., 2003), this is classed as direct secondary damage. Thus, oil damage may therefore be classed as direct primary (when the oil tank bursts) as well as direct secondary damage (when the oil contaminates walls).

When it comes to measuring direct monetary damage to buildings, most studies infer the monetary losses from the use and/or type of the building and the inundation depth (see also Wind et al., 1999; Zhai et al., 2005; Nascimento et al., 2006). Flood damage functions are traditionally estimated by an empirical flood depth-damage curve, where flood depth is the only factor in the flood-damage function (Chang et al., 2008). The recent international literature, mostly referring to the stage-damage curves by Penning-Rowsell and Chatterton (1977) and extending it (see, e.g., by Parker et al., 1987, 2007; Penning-Rowsell and Green, 2000), also uses water levels as one of the main hazard parameters, once the use category is identified. In Chang et al. (2008) flood damage is determined by water depth and geographical zone, whereby, in accordance with current research literature, flood depth is chosen as principal factor for assessing flood damage. Thieken et al. (2005) take water level along with flood duration and contamination (by oil/petrol amongst other things) as the most influential factors for building and content damage. However, the study at hand relies on newly available data on damage and water depths (measured in cm) for one general use category (residential buildings) only, and distinguishes within this category (e.g. cellar, ground floor and adjoining buildings, e.g. garages). More precisely, we analysed damage to flooded dwellings in the aftermath of a flood event in one municipality in Austria, i.e. a dam breach on the river March in April 2006 (Amt der NÖ (Niederösterreichischen) Landesregierung, 2006a). Here, contamination by oil was locally perceived as a major cause of high damage. This was one reason for us to follow Thieken's above mentioned suggestion and to investigate this issue further and provide initial quantifications of such damage for Austria.

In the recent literature (see, e.g. Büchele et al., 2006; Pflügner and Schmidtke, 2007), incorporating a square-root function of water depth was found to provide good results in Germany in explaining damage along with a constant minimum damage (Pflügner and Schmidtke, 2007). This functional form has also been adopted for Austria, but not empirically estimated so far. Therefore, a main aim of the present paper is to test whether a similar functional form can be derived for the dam breach scenario in Austria. This is carried out in Sect. 5 below. Before this, relevant data is described in Sect. 3, and methodology in Sect. 4. Finally, the estimated flood damage function is cross-validated in Sect. 6, where we also undertake the useful exercise of relating the potential flood damage derived from the absolute damage function to the general maximum damage (loss) potential in the case study area. This is why we now turn to an estimation of the maximum damage potential, which is also helpful as a further description of the case study area before carrying out the damage function estimation.

2 Maximum loss potential – in the case study area and in Austria

This section deals with the case study area's maximum damage (loss) potential. While this is not directly used here in estimating the flood damage curve, it does provide useful insight into the relation between the estimated flood damage to buildings and the monetary values of the buildings at risk, estimated before the flood event took place.

[1] Meyer and Messner (2005, p. 2), for example, write that "[. . .] flood damage refers to all varieties of harm caused by flooding."

Table 1. Maximum damage potential in the HQ200 risk zones in the provinces of Austria.

Province	Residential buildings (based on the raster data set)	Number of apartments	Maximum damage potential in millions EURO
Burgenland	3851	17 101	2482
Carinthia	9349	27 746	8065
Lower Austria	33 323	88 197	27 958
Upper Austria	19 060	58 821	18 447
Salzburg	8157	53 539	17 577
Steiermark	19 131	58 728	14 351
Tyrol	10 137	64 439	21 120
Vorarlberg	3533	25 446	8287
Vienna	2688	14 817	5529
Austria	109 229	408 834	123 817

Source: Statistics Austria, Wohnungs- und Gebäudezählung, 2001, and Fachverband der Immobilien- und Vermögenstreuhänder, Immobilienpreisspiegel, 2007, Zoning information: HORA (2007).

Table 2. Residential buildings in the risk zones and their market value in the case study area (Dürnkrut in Lower Austria).

Risk zone	Residential buildings	Number of apartments	Maximum damage potential (building stock value) in million EURO
HQ30	93	99	23
HQ100	116	123	28
HQ200	126	132	32
Total community	887	1150	283

Source: Statistics Austria, Wohnungs- und Gebäudezählung (2001), zoning information: HORA (2007), own calculations.

The maximum damage (loss) potential is considered to equal the value of all assets at risk and can be assessed in order to derive the expected flood damage under different scenarios, whereby the use of flood damage curves is only one possible option (Meyer and Messner, 2005). Similarly to Briene et al. (2002) (as summarized by Meyer and Messner, 2005), median market values were used in the assessment of the maximum damage amount of residential dwellings in the case study area in Lower Austria (Municipality of Dürnkrut) and in Austria as a whole. Inventories were valued on the basis of standardized valuation methods used by insurance companies (Generali Versicherung AG, 2007, see also Prettenthaler et al., 2009).

In Prettenthaler et al. (2009), the raster data set of buildings in Austria (Statistik Austria, 2001), to which median housing values (based on the data published in Fachverband der Immobilien- und Vermögenstreuhänder, 2007) were assigned, was merged with data underlying the national flood risk zoning system (HORA – Hochwasserrisikozonierungssystem Austria, 2007), using raster-based GIS. In most parts of the covered area, this zoning system does not account for the protective function of dams and other technical flood prevention measures (such as different types of dams). This feature makes the general application of the existing HORA (2007) data controversial in flood risk measurement. However, for the case of dam breach scenarios, this tool, as it stands, is exactly what evaluation of maximum loss potential requires, as is verified by the endorsement of the Austrian insurance industry. Table 1 summarizes the estimated values of residential buildings at risk in the HORA (2007) HQ200 risk zones[2] for all Austrian provinces, resulting in a maximum damage potential of € 123.8 billion in the HQ200 risk zones all over Austria. This amounts to 12.6% of the value of the total Austrian residential building stock.

In the case study area Dürnkrut (with a surface area of about 30.4 square kilometres) the value of residential dwellings at risk (HQ200) amounts to about € 32 million that is 11.3% of the value of the total residential building stock[3]. The number of residential dwellings at risk is 126 (including 132 apartments) in the HQ200 risk zones in Dürnkrut. Table 2 displays the number of buildings and apartments in all 3 risk zones (HQ30, HQ100, HQ200) and the respective loss potential.

[2]The HQ200 risk zones are those zones where floods are expected once in 200 years, i.e. where a flood event occurs with the annual probability of 0.5%.

[3]Residential dwellings represent the prevailing building type in the case study area Dürnkrut.

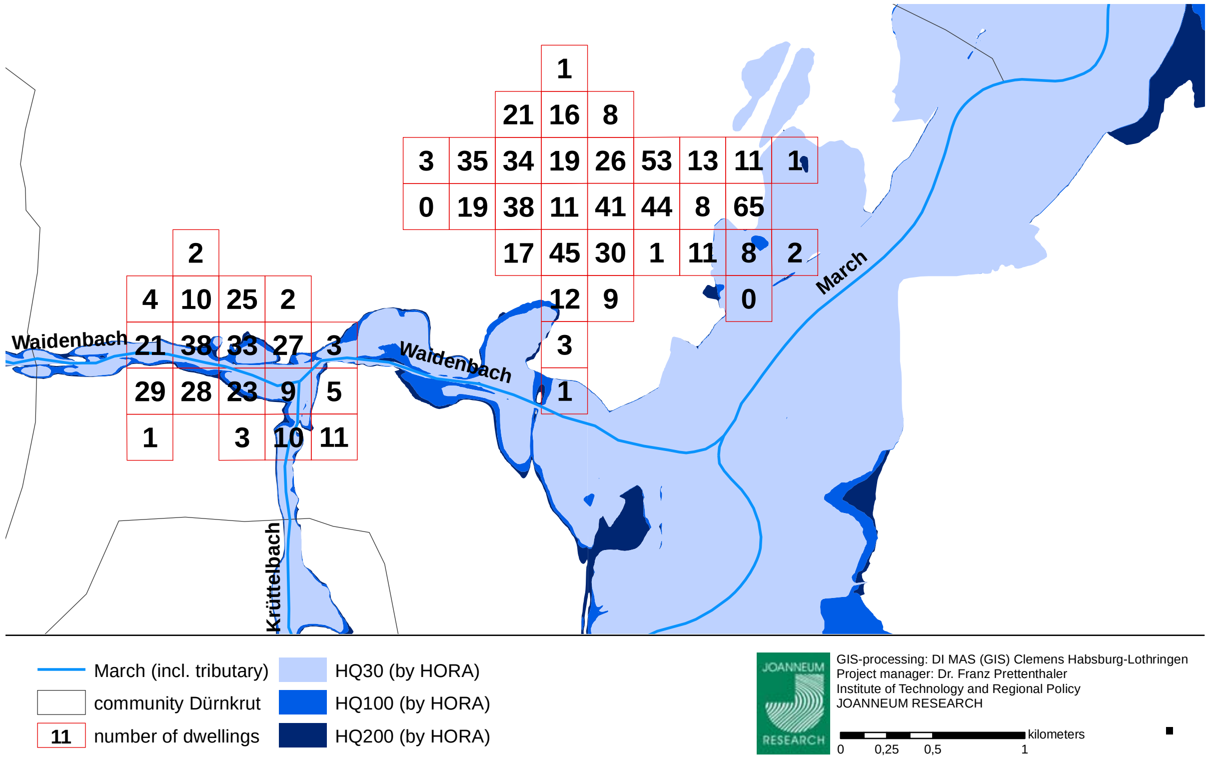

Fig. 1. Spatial distribution of residential apartments in the HQ30, the HQ100 and the HQ200 risk zones. Data source: Statistics Austria, Wohnungs- und Gebäudezählung (2001), and HORA – Hochwasserrisikozonierungssystem Austria.

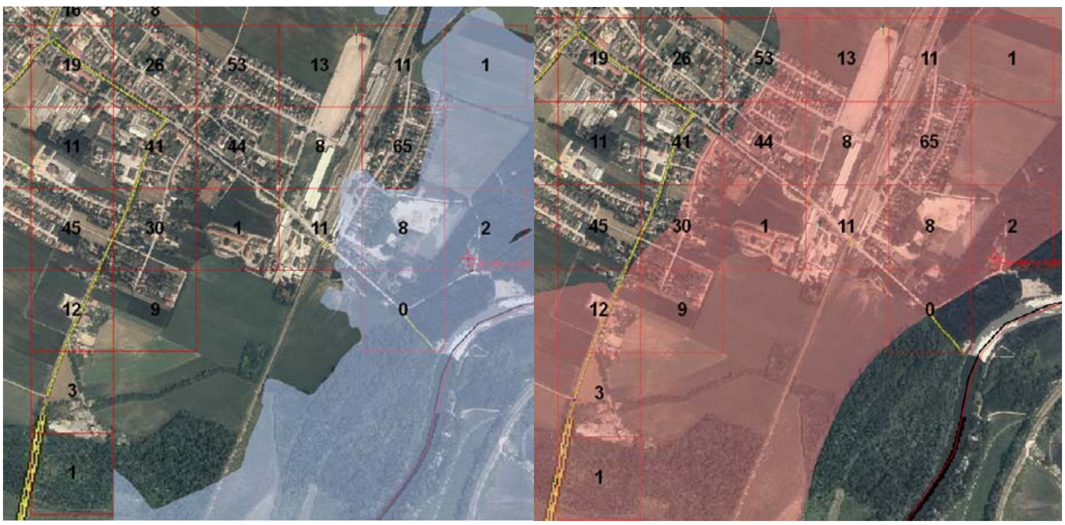

Fig. 2. HORA HQ200 risk zones (left hand side, blue area) and ex post water line modelling – WAL zones (right hand side, red area) in the flooded area of Dürnkrut. Data source: HORA – Hochwasserrisikozonierungssystem Austria and firm RIOCOM.

Figure 1 exhibits the spatial distribution of apartments in the HQ200 risk zones along the River March, whereby the numbers in the boxes represent the quantity of existing residential apartments per raster cell (Statistik Austria, 2001). Figure 2, in contrast, displays the 19 raster cells in the flooded area. The red area on the right hand side approximates the flooded area in 2006 (according to the ex post water line modelling (Wasseranschlaglinie – WAL) by RIOCOM), whereas the blue area on the left hand side delineates the HQ200 risk zones (according to HORA). The total market value of the 234 residential buildings in the WAL risk zones amounts to about € 76 390 000 whereas the total market value of the residential buildings within the affected area in the HQ200 risk zone amounts to about € 8 000 000 based on the real estate market prices in 2007 (Fachverband der Immobilien- und Vermögenstreuhänder, 2007). Thus, the dam breach event in 2006 was more severe and affected a larger area than a HQ200 event.

It needs to be noted that the proportion of the affected residential buildings and the number of apartments in the partially flooded cells (Fig. 2) was estimated statistically. The number of apartments with an oil heating system amounts to 185 in the flooded areas (according to the WAL risk zones, Statistik Austria, 2001). This is a high number, considering that secondary oil damage in buildings can translate into very high monetary losses. Müller (2000) found that oil damage can lead to three times higher damage values than regular damage. Since only the number of apartments with an oil heating system is available in the WAL risk zones and each residential building is presumed to have about 1.4 apartments (there are 323 apartments per 234 residential buildings in the WAL risk zones), we assume that the number of residential buildings with an oil heating system is about 132, based on census data for 2001 (Statistik Austria, 2001).

One possibility of estimating the potential flood damage is to overlay the maximum loss potential by a relative flood damage function (see e.g. Meyer and Messner, 2005). In this paper, however, we choose another approach by estimating an absolute flood damage function to forecast the flood damage potential. Nevertheless, we then compare it to the maximum damage potential in the WAL risk zones where the flood event took place. Hence, our flood damage function is tested in two ways; firstly, by a cross-validation procedure and secondly, by its application in estimating the flood damage potential in the case study area and comparing it to the maximum damage potential.

3 The data

In April 2006, a flood event occurred in the municipality of Dürnkrut, where a dam breach led to total damage of € 14.2 million (Amt der NÖ Landesregierung, 2006a). Given that Dürnkruts's maximum damage potential (HQ200) is € 32 million, the total amount of the damage caused by the event in 2006 was considerable – almost 45% of the maximum damage potential (HQ200). The maximum damage potential (HQ200) is usually considered a good estimate for the value at risk in specific municipalities. However, as noted above, the event in 2006 transcended the HQ200 risk zone and, as a proportion of the buildings actually affected, destroyed 18.6% in value terms.

Information on damage to buildings (denoted by D and including cellar and ground floor damage and damage to adjoining buildings) as well as on the corresponding water depths in each building unit and square meters of the flooded surfaces was obtained from the provincial government of Lower Austria. From the total population of 249 damaged buildings, 16 observations had to be eliminated from the sample due to the lack of exact indications of water depth etc. This leaves total damage at € 13.4 million after the sample reduction.

In the remaining sample of 233 damaged dwellings, 144 damage cases were observed in adjoining buildings (such as garages), 135 in ground floors and the major part of damage occurred in cellars (221). In fact in 49 dwellings, cellar damage was the only damage observed. Data on flood water depth in each building unit are given in cm. If water was in the ground floor and the house had a cellar, we assumed the cellar to be full of water. In those cases, where the cellar was completely full of water, water depth was assumed to amount to about 3 m, which seems to be a reasonable value, slightly above the water depths of, e.g., 2.5 or 2.1 m which were indicated in cases where the cellars were not full of water. As expected, generally mean water depth in the cellars was much higher than in the ground floors and the adjoining buildings. However, it needs to be noted, that not all flooded buildings had a cellar. For such cases only water depth for the ground floor was given. Table 3 presents the descriptive statistics on the attributes available for each damage case and Fig. 6 illustrates the aggregated flood damage.

The damage was estimated by the local authorities in two ways: partly by expert judgement, supported by standardized guidelines set by the provincial government of Lower Austria, and partly on the basis of more sophisticated individual expert surveys, especially when secondary oil and static damage caused by flood water had been observed. More specifically, regular damage to buildings, adjoining buildings, inventory, etc. was assessed on the basis of predetermined reference damage values, which are adapted annually. Total damage, static damage, damage to special building equipment and oil damage were, in contrast, valued on the basis of the replacement or restocking costs. The reference damage values in € per square meters of cellars, ground floors and adjoining buildings differ (as a result of deductions and surcharges) according to the quality of the equipment, the construction category and threshold values of water depth above the floor top level. In the assessment, the usable surface was also evaluated in a specific manner. The damage assessment was carried out by the so-called local damage assessment commissions ("örtliche Schadenserhebungskommissionen"), involving certified surveyors (Amt der NÖ (Niederösterreichischen) Landesregierung, 2005, 2006). Private households informed commission surveyors of the water level in the ground floors, the cellars and adjoining buildings. The damage valuation method used by the NÖ (Niederösterreichische) Landesregierung complies with the valuation concept used in the international literature on flood damage assessment. In the literature, the restoration cost approach or the cost of repairs plus the loss in value of

Table 3. Descriptive statistics of parameters/attributes for the damage data.

	Damage in €	W_{GF}	W_{AB}	W_{C}	SQM_{GF}	SQM_{AB}	SQM_{C}	D_{oil}
Mean	57 718	0.39	0.86	2.07	50.95	28.48	72.90	0.17
Median	44 691	0.05	0.80	2.20	58.00	18.00	71.00	0.00
Maximum	231 684	1.80	3.00	3.00	221.00	714.00	240.00	1.00
Minimum	1694	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Std. dev.	47 057	0.51	0.84	0.82	50.92	54.68	42.97	0.38
Sum	13 448 399	90.21	197.83	482.48	11 871.00	6636.00	16 912.30	40.00
Jarque Bera	90	56.27	17.59	50.84	15.22	10 8941.40	12.38	128.10

Data source: Amt der NÖ Landesregierung, Abteilung Landwirtschaftsförderungen (2006a).

the repaired item (SCARM, 2000) currently prevails. Here, oil/static damage is assessed according to the restoration cost approach and regular damage is valued according to criteria developed by the professional judgement of the construction authority (Amt der NÖ (Niederösterreichischen) Landesregierung, 2005). Another possibility entails conducting relatively costly interviews. In Kreibich et al. (2005) and Thieken et al. (2005) computer-aided telephone interviews were undertaken in flood-affected private households after the flood event, whereby besides assessing damage to buildings and contents, information on a variety of factors, such as variables describing flood impact, precaution, and preparedness as well as characteristics of the affected buildings, etc. was gathered. We also need to note here that we randomly interviewed affected individuals who complained about the deficiency of the dam as the main public precautionary measure. However, due to the relatively small area of Dürnkrut and the relatively low number of interviewees, damage values gained through surveys are likely to be subject to bias. Moreover, although the incorporation of more factors improves the statistical significance and model fit, the use of the smallest possible number of independent variables facilitates data collection and aids damage prediction (Chang et al., 2008).

While we largely accepted the statements by local government experts that assessed tangible damage values can be considered real historical flood damage values, we still proceeded with caution. It is well known in the literature that damage data gained by interviews/surveys may be biased. For instance, Thieken et al. (2005, p. 11) confirmed that "stated damage regularly tops the denoted values." According to Thieken et al. (2005) data are more reliable where interviewees claim damages from insurance and governmental funds. Thus, the fact that the data used within this paper stem from claims on public funds lends support to their reliability.

4 Methodology

4.1 Estimation method

The following section presents the definition of an equation for the absolute flood-damage function by means of parametric least squares regression analyses (also frequently applied in the flood damage literature, see, e.g., Nascimento et al., 2006; Chang et al., 2008) on the basis of available information on regular and oil/static damage in euros, along with the variables water depth in the cellar, water depth in the ground floor, water depth in the adjoining building, and the square meters (flooded surface) in the cellar, the ground floor and the adjoining building.

4.2 Definition of variables

As mentioned above, regular damage was estimated according to the standardized guidelines set by the provincial government of Lower Austria (Amt der NÖ Landesregierung, 2006). At least 20% of the damage figures collected were found to exhibit much higher values compared to the sample mean – a clear reflection of the impact of oil/static damage.

Figures were estimated on the basis of detailed damage surveys (reflecting oil and static damage, where the experts also clearly indicated a different cause for the damage other than mere water depth, e.g. the existence of unprotected oil tanks in some cases, and either higher water speed or different construction material in others). Thus, it was clear that we had to take these other factors into account in addition to water depth. Here, differentiation between regular damage on the one hand and oil and static damage on the other hand was central. Despite the initial lack of exact data concerning oil and static damage, it was possible to create a dummy variable (D_{oil}) to cover extreme deviations from the sample mean. The dummy takes on the value of 1 where oil/static damage is assumed, and a value of 0 otherwise. Dummies were set for all damage observations, for which no relationship to flood water depth is apparent. In fact, original data providers confirmed for every case where we had set a dummy value of 1, that damage appraisers had

Table 4. Regression analysis (Eqs. 1, 1a, 1b and 1c).

Dependent variable: damage in €; sample=233; included obs.=88					
Equation (1) (lin-log function)			Equation (1a) (lin-lin function)		
Variable and constant	Coefficient	t-statistic (abs.)	Variable and constant	Coefficient	t-statistic (abs.)
C	54 296.22	9.8	C	16 874	4.7
$\log(W_{GF}) \cdot SQM_{GF} \cdot D_R$	81.32	2.6	$W_{GF} \cdot SQM_{GF} \cdot D_R$	341	8.5
$\log(W_C) \cdot SQM_C \cdot D_R$	161.24	1.6	$W_C \cdot SQM_C \cdot D_R$	76	3.8
$\log(W_{AB}) \cdot SQM_{AB} \cdot D_R$	338.99	3.2	$W_{AB} \cdot SQM_{AB} \cdot D_R$	123	2.7
$\log(W_{GF}) \cdot SQM_{GF} \cdot D_{oil}$	−31.68	0.5	$W_{GF} \cdot SQM_{GF} \cdot D_{oil}$	415	5.6
$\log(W_C) \cdot SQM_C \cdot D_{oil}$	1067.44	7.9	$W_C \cdot SQM_C \cdot D_{oil}$	433	9.6
$\log(W_{AB}) \cdot SQM_{AB} \cdot D_{oil}$	282.63	5.2	$W_{AB} \cdot SQM_{AB} \cdot D_{oil}$	62	2.2
R^2=.71, R^2-adj.=.69 Akaike=23.3, F-stat.=33.12, JB=1.2			R^2=.76, R^2-adj.=.75, Akaike=23.0, F-stat.=116.8, JB=52.2		
Equation (1b) (lin-log function)			Equation (1c) (square root function)		
Variable and constant	Coefficient	t-statistic (abs.)	Variable and constant	Coefficient	t-statistic (abs.)
C	94 423.59	5.3	C	−289.63	0.1
$\log(W_{GF}) \cdot D_R$	9211.40	3.9	$\text{sqr}(W_{GF} \cdot SQM_{GF}) D_R$	4661.38	10.8
$\log(W_C) \cdot D_R$	−33 306.33	1.9	$\text{sqr}(W_C \cdot SQM_C) \cdot D_R$	1796.52	5.3
$\log(W_{AB}) \cdot D_R$	14 232.70	4.3	$\text{sqr}(W_{AB} \cdot SQM_{AB}) \cdot D_R$	1478.32	3.3
$\log(W_{GF}) \cdot D_{oil}$	1964.98	.2	$\text{sqr}(W_{GF} \cdot SQM_{GF}) \cdot D_{oil}$	5514.18	3.9
$\log(W_C) \cdot D_{oil}$	51 854.84	1.6	$\text{sqr}(W_C \cdot SQM_C) \cdot D_{oil}$	6733.61	9.2
$\log(W_{AB}) \cdot D_{oil}$	−3691.78	.2	$\text{sqr}(W_{AB} \cdot SQM_{AB}) \cdot D_{oil}$	1295.82	1.4
R^2=.67, R^2-adj.=.64 Akaike=23.4, F-stat.=26.95, JB=20.5			R^2=.80, R^2-adj.=.80 Akaike=22.8, F-stat.=148.1, JB=43.7		

Note: W_{GF}, W_C, W_{AB} and SQM_{GF}, SQM_C, SQM_{AB} denote the water depths in meters and usable surface in square meters, respectively, whereas D_R (D_{oil}) indicates the dummy variable for regular (oil/static) damages.
Data source: Amt der NÖ Landesregierung, Abteilung Landwirtschaftsförderungen (2006a), own calculations.

assessed either static or oil damage. Thus, the separation of the two categories of damages was not an ad hoc decision by the current authors, but a realistic reflection of actual building damage. Only where the flood caused either static damage or oil spills within the building, were the expected costs for reconstruction (which formed the basis of damage surveys) much higher than in all the other cases where the damage occurred from mere flooding of the building. As we discuss below in more detail, the respective dummy variables were able to explain this variation in the dependent variable very well (t-statistic: 4.9 in Eq. 2 (Table 5)). We also set a complementary dummy variable, denoted by D_R. This takes on the values 1 for regular damage and 0, otherwise.

4.3 Choice of the regression specification

4.3.1 Relationship between the variables

When relating both types of damage (static and oil damage along with the regular damage) to water depth in meters per dwelling (accumulated for all building units of the dwelling: the cellar, the adjoining buildings and the ground floor), accumulated water depth explains a smaller part of total variability than volume, as can be deduced by visual interpretation of Fig. 3. Moreover, excluding oil and static damage from the sample improves explanation of total variability by the accumulated water depth (but also by the accumulated water volume), as evidenced by the change in kernel fit[4] (see Fig. 3 vs. Fig. 4). Remaining outliers may be partly explained by differences in the qualities of the building units' furnishings. Figure 5 illustrates a simple lin-lin accumulated water-depth-damage curve for all building units, and the corresponding lin-lin accumulated water-volume-damage curve in the scatter plots. As can be observed from the scatter plots, variability is reduced when water volume is used, in comparison to that found using water depth.

Note however, that the scatter plots with nonparametric kernel regressions (Figs. 3 and 4) as well as those with linear regression (Fig. 5) only informally represent the relation of the aggregated damage to the aggregated water depth/volume to get a general idea of the data. The aim of the regression

[4] Eviews 5.1 data-based automatic bandwidth selection, using Silverman's method (1986), was applied for fitting the kernel curve.

Table 5. Regression analysis (Eqs. 2, 2a, 2b and 2c).

Dependent variable: damage in €; sample=233; included obs.=230 (231 in Eq. 2b)					
Equation (2) (lin-lin function)			Equation (2a) (lin-log function)		
Variable and constant	Coefficient	t-statistic (abs.)	Variable and constant	Coefficient	t-statistic (abs.)
C	12 991	4.0	C	−40 999	1.8
D_{oil}	120 546	4.9	D_{oil}	180 265	7.6
$W_{\text{GF}} \cdot SQM_{\text{GF}} \cdot D_{\text{R}}$	358	2.8	$\log(W_{\text{GF}} \cdot SQM_{\text{GF}}) \cdot D_{\text{R}}$	9605	4.6
$W_{\text{C}} \cdot SQMc \cdot D_{\text{R}}$	124	9.0	$\log(W_{\text{C}} \cdot SQMc) \cdot D_{\text{R}}$	8407	2.2
$W_{\text{AB}} \cdot SQM_{\text{AB}} \cdot D_{\text{R}}$	93	15.0	$\log(W_{\text{AB}} \cdot SQM_{\text{AB}}) \cdot D_{\text{R}}$	7397	2.4
R^2=.73, R^2-adj.=.72, Akaike=23.10, F-stat.=151.3, JB=158.6			R^2=.71, R^2-adj.=.69, Akaike=23.25, F-stat.=151.2 JB=17.8		
Equation (2b) (square root function)			Equation (2c) (square root function)		
Variable and constant	Coefficient	t-statistic (abs.)	Variable and constant	Coefficient	t-statistic (abs.)
C	6251.45	1.0	C	−616.62	0.2
D_{oil}	127 285.10	13.6	D_{oil}	134 153.10	16.4
sqr(W_{GF})·D_{R}	34 736.94	7.7	sqr($W_{\text{GF}} \cdot SQM_{\text{GF}}$)·$D_{\text{R}}$	4672.77	10.9
Sar(W_{C})·D_{R}	11 377.74	2.5	Sar($W_{\text{C}} \cdot SQMc$)·D_{R}	1818.28	5.7
sar(W_{AB})·D_{R}	10 355.68	3.5	sar($W_{\text{AB}} \cdot SQM_{\text{AB}}$)·$D_{\text{R}}$	1481.07	3.4
R^2=.69, R^2-adj.=.68 Akaike=23.23, F-stat.=125.6 JB=88.0			R^2=.74, R^2-adj.=.74 Akaike=23.05, F-stat.=162.7, JB=196.		

Note: W_{GF}, W_{C}, W_{AB} and SQM_{GF}, SQM_{C}, SQM_{AB} denote the water depths in meters and usable surface in square meters, respectively, whereas D_{R} (D_{oil}) indicates the dummy variable for regular (oil/static) damage.
Data source: Amt der NÖ Landesregierung, Abteilung Landwirtschaftsförderungen (2006a), own calculations.

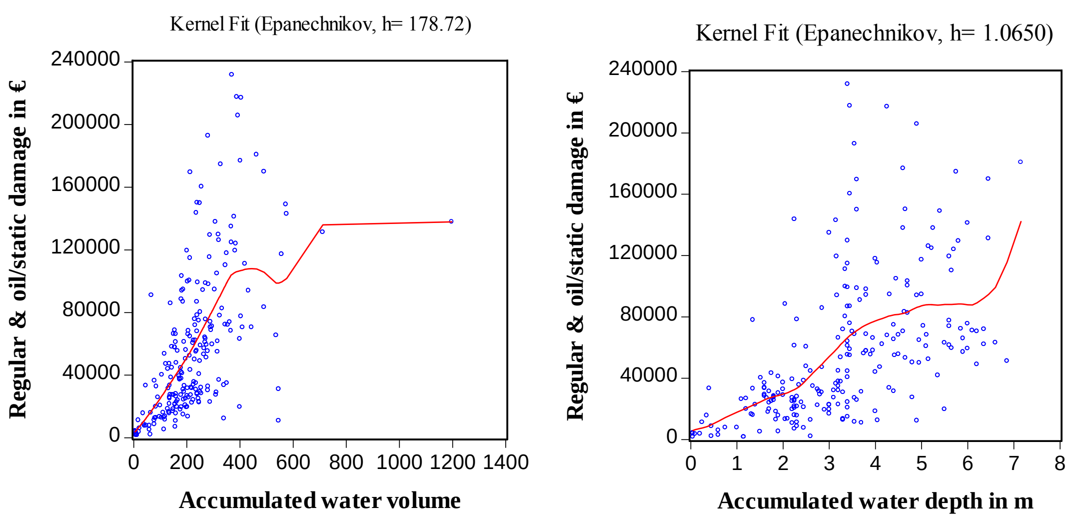

Fig. 3. Scatter plot with the water-volume- and water-depth-damage function (Epanechnikov-kernel with bandwidth h) for all damage (regular as well as oil/static damage). Data source: Amt der NÖ Landesregierung, Abteilung Landwirtschaftsförderungen (2006a).

analyses, to which we turn now, however, is estimation of individual coefficients of the water depth/volume in the cellar, ground floor and the adjoining buildings in a disaggregated way.

4.3.2 A priori assumptions on the functional form

The a priori assumptions concerning the functional form of the parametric OLS (e.g., on the linear relationship between water and damage for regular damage and the reduced

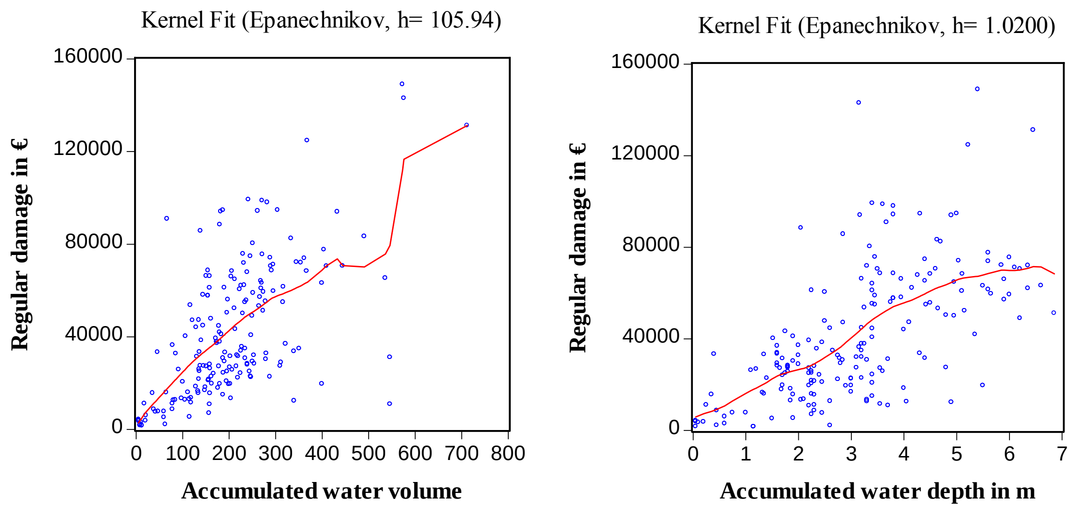

Fig. 4. Scatter plot with the water-volume- and water-depth-damage (Epanechnikov-kernel with bandwidth h) for regular damage. Data source: Amt der NÖ Landesregierung, Abteilung Landwirtschaftsförderungen (2006a).

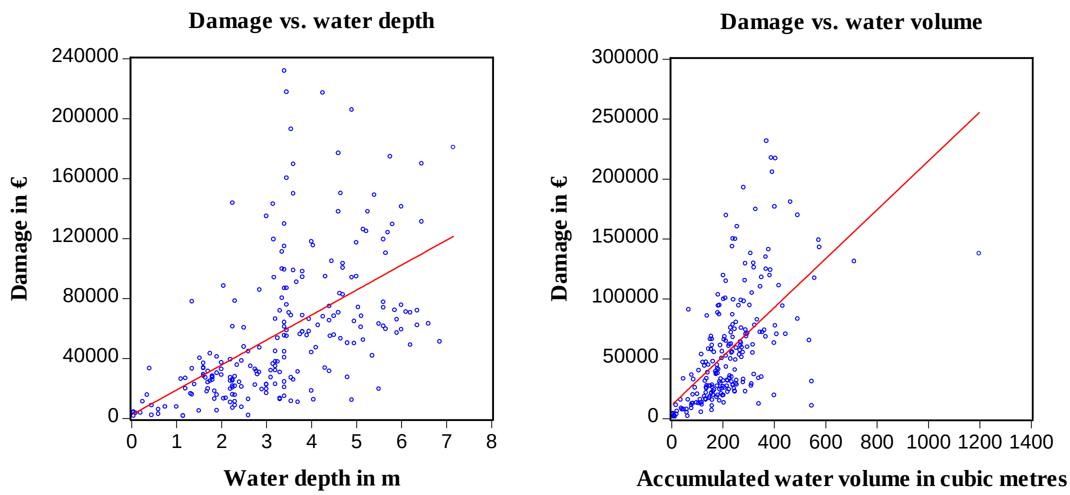

Fig. 5. Accumulated lin-lin-water-volume-damage curve and accumulated lin-lin-water-depth-damage curve (accumulated for all building types). Data source: Amt der NÖ Landesregierung, Abteilung Landwirtschaftsförderungen (2006a).

water depth dependence of the amount of damage caused by oil) were based on previous flood literature findings (e.g., Pflügner and Schmidtke, 2007) as well as on the latest directive on preparing cost-benefit analyses for flood protection in Austria (Kosten-Nutzen Untersuchungen im Schutzbau Richtlinie, see Lebensministerium, 2008). It was our intention to test the practical applicability of such legally binding specifications. Secondly, the choice of the functional form was influenced by the structure of the information obtained from the experts concerned (Amt der NÖ Landesregierung, 2006a), and was also intuitively derived from data analysis by means of graphical representations (Figs. 3, 4 and 5) as further explained below. In line with the choice of the appropriate functional form suggested by the literature, the variables and the interaction of different variables were tested for significance. The main functional forms tested are presented in Tables 4 and 5.

According to Pflügner and Schmidtke (2007) and Lebensministerium (2008), damage functions usually exhibit a constant minimum damage $S_{\min}$ in addition to a square root function of water depth. $S_{\min}$ refers to the damage that occurs independently of the water depth if a building is flooded and varies with the building type. Büchele et al. (2006), in contrast, propose a square root function of water depth to explain damage, without use of a minimum damage component in the function. Other authors suggest a lin-log functional form, also including constant minimum damage (Nascimento et al., 2006).

4.3.3 Selection of the appropriate functional form on the basis of relevant literature and statistical tests for functional form misspecification

Based on these findings, we tested different functional forms with and without the inclusion of a constant ($S_{\min}$), with and without the consideration of oil/static damage as a dummy variable, and using either water depth or water volume as independent variables. Throughout the paper estimators consistent with White-heteroskedasticity were used.

Firstly, we found that the product of square meters and water depth (i.e. water volume) as explanatory variable for regular damages performed much better in the regressions (in terms of increased explanatory power) than square meters and water depth individually (additionally, the inclusion of one interaction variable instead of two variables reduces the degrees of freedom of the model) (see Eq. (1) versus Eq. (1b) in Table 4). Visual examination of kernel fit suggests that substantial information is lost when only water depth rather than water volume is used as explanatory variable. See the impact on regular damage (Fig. 4) and regular damage including oil and static damage (Fig. 3).

Secondly, the separate inclusion of oil/static damages, D_{oil}, as a dummy variable (see Eqs. (2) and (2a) in Table 5) and not as a multiplier with water volume in the lin-lin regression form (see Eq. (1a) in Table 4) eliminates the problems obtaining in Eq. (1a) of general functional form misspecification (as indicated by Ramsey's RESET test for misspecification between the dependent and the independent variables). The inclusion of the D_{oil} constant to cover higher damage resulting from static or oil damage, is also supported by the fitted curves (Figs. 3, 4 and 5) where particularly for smaller levels of damage a positive linear relationship between water depth/volume and damage exists. On the other hand, higher damage seems to correlate less well with water depth or volume and hence appears to be less water level (volume or depth) dependent. These apparently different correlations between oil/static and water depth or volume, and regular damage and water depth or volume, imply that oil/static damage and regular damage should be treated separately in the regression equation.

Thirdly, several functional forms proposed in the research literature were tested, whereby the ultimate choice of the functional form was based on statistical criteria, on ease of potential flood damage curve application, as well as on the theoretical significance of including minimum damage.

On testing the lin-log functional form proposed by Nascimento et al. (2006)[5], the square root function proposed by Lebensministerium (2008)[6], and the lin-lin functional form[7], we concluded that the lin-lin function form, which includes two constants, one for general minimum damage and one for oil/static damage, performed best. The main conclusions resulting from testing the functional forms proposed by the literature are as follows:

- The lin-lin functional form (Eq. 2 in Table 5) outperformed the lin-log function (Eq. 2a in Table 5) in terms of best fit criteria (see, e.g., R-squared adjusted) as well as in terms of practical application of the flood damage curve (this is related to the negative constant (representing the minimum damage) in Eq. 2a in Table 5).

- By taking the square root of the respective explanatory variables, Ramsey's RESET test indicated that the null hypothesis of no specification errors in the equation is not rejected for Eq. (1c) in Table 4 and Eq. (2b) in Table 5.

- The lin-lin Eq. (2) in Table 5 outperformed Eq. (1) in Table 4 where the logarithm of water depth in regular damage and oil/static damage for individual building units (the cellar, the adjoining building and the ground floor) was multiplied by the flooded surface, e.g., on the basis of the R-squared and the Akaike criterion.

- Other functional forms, such as the log-log and the log-lin performed worse in terms of explanatory power and general specification error tests.

- When including the square root of water volume instead of the square root of water depth as explanatory variable in Eq. (2) (see Eq. 2c in Table 5), the constant became negative, while the explanatory power of the regression was slightly improved (i.e., the R-squared increased by 2%). The square root of water volume neither complies with the theory proposed by Lebensministerium (2008) (where basically the square root of water depth along with constant minimum damage explains the total damage), nor is it advantageous in terms of practical applicability.

5 Estimation results

In this section, the two final regression Eqs. (1) and (2) are presented, whereby Eq. (2) was found to be preferable:

In Eqs. (1) and (2), $W_{\text{GF}}, W_{\text{C}}, W_{\text{AB}}$ and SQM_{GF}, SQM_{C}, SQM_{AB} denote the water depths in meters and usable surface in square meters, respectively, in the ground floors, cellars, and adjoining buildings. The error term is denoted by ε.

$$\begin{aligned} D = {} & c+\log(W_{\text{GF}})\cdot SQM_{\text{GF}}\cdot D_{\text{R}}+\log(W_{\text{C}})\cdot SQM_{\text{C}}\cdot D_{R} \\ & +\log(W_{\text{AB}})\cdot SQM_{\text{AB}}\cdot D_{R} \\ & +\log(W_{\text{AB}})\cdot SQM_{\text{AB}}\cdot D_{\text{R}} \\ & +\log(W_{\text{GF}})\cdot SQM_{\text{GF}}\cdot D_{\text{oil}}+\log(W_{\text{C}})\cdot SQM_{\text{C}}\cdot D_{\text{oil}} \\ & +\log(W_{\text{AB}})\cdot SQM_{\text{AB}}\cdot D_{\text{oil}}+\varepsilon \qquad (1) \end{aligned}$$

[5] See Eqs. (1) and (1b) in Table 4 as well as (2a) in Table 5.
[6] See Eq. (1c) in Table 4 as well as (2b) and (2c) in Table 5.
[7] See Eq. (1a) in Table 4 and (2) in Table 5.

$$D = c + D_{\text{oil}} + W_{\text{GF}} \cdot SQM_{\text{GF}} \cdot D_{\text{R}} + W_{\text{C}} \cdot SQM_{\text{C}} \cdot D_{\text{R}} + W_{\text{AB}} \cdot SQM_{\text{AB}} \cdot D_{\text{R}} + \varepsilon \quad (2)$$

Again, the multiplicative link between square meters and water depth (i.e. water volume) rather than the separate inclusion of each variable in the regression performed better in both Eqs. (1) and (2). However, consideration of D_{oil} as a constant (Eq. 2) and not as multiplicatively linked with water volume (Eq. 1), resulted in best performance in terms of general specification tests (e.g., Ramsey Reset Test and best fitting criteria). Since static and oil damage were carefully assessed in detailed surveys, there is no doubt about the reliability of the data. Given the additional arguments concerning e.g. convenience and ease of applicability, we suggest Eq. (2) for further application in damage assessment, assuming cross-validation in Sect. 6 below does not indicate otherwise. As already mentioned, Eqs. (1) and (2) are based on research findings (e.g., Lebensministerium, 2008) stressing the importance of the inclusion of positive minimum damage – here, for the two damage categories (regular and oil/static damage) – in the regression function, where the variable part of the damage should vary according to water depth, generally considered to be among the most important flood damage determinants (see Tables 4 and 5). The constant c in both equations stands for S_{min}, in line with Lebensministerium (2008); and the fit of both equations is satisfactory. However, Eq. (2) performs better in terms of explanatory power. As expected, if the square meters are removed from the models, the explanatory power of the regressions is substantially reduced.

In Eq. (2), residuals are not normally distributed (attributable to the outliers in the underlying data set). If residuals are not normally distributed, F and t statistics are invalid. However, removing outliers to obtain normally distributed residuals did not meaningfully change regression results, so they were maintained in the data set. We rely on the Gauss-Markow assumptions met in the estimation of OLS and on the central limit theorem as regards the test statistics, and accept Eq. (2). Also by plugging the historic data into the estimated Eq. (2), we found that the estimated D only deviates negligibly from the total actual damage in the case study area. Separate consideration of both oil and static damage in this paper, shows that depth of flood water explains the variability of the damage to a great extent in the underlying data set.

6 Cross-validation of the flood damage function and estimation of the potential flood damage

Since no independent data set was available in order to test the performance and reliability of the model, we used a variant of split-half cross validation procedure on a data set subsample (see e.g. Picard and Berk, 1990). First, the total sample approximating the total population was reduced by randomly drawing approximately 50% so as to obtain a representative test sample set (N=117). Here, the Eq. (2) model was found to predict the variation in the dependent variable quite well (Theil Inequality Coefficient: 0.17 (covariance proportion: 0.91)) with a root mean squared error (RMSE) of 22 938 and a mean absolute error of 17 683. Applying the same model to the other 50% of the data, the Theil Inequality Coefficient and the covariance proportion of the validation sample set were 0.16 and 0.93, respectively, with a root mean squared error of 23 455 and a mean absolute error of 17 766 (see Table 6). It needs to be noted that more than 68% (for more on this rule of thumb see Barretto and Howland, 2006) of the points from the regression line fall within the root mean squared error for both data sets. More precisely, 82% of the data points deviating the regression line using the testing set fall within the ±1 RMSE band and 77% of the data points deviating from the regression line using the validation set fall within the ±1 RMSE band.

Generally, the Theil Inequality Coefficient is between zero and one, whereby zero indicates a perfect fit. The covariance proportion measures the unsystematic bias, which is relatively high in comparison to remaining bias and variance proportion. Since most of the bias is concentrated in the covariance proportion, the high systematic bias is indicative of good forecast performance.

How would our function have fared if we had known ex ante the exact area of inundation (now given by the WAL zone) and we had had to predict the damage from the 2006 event? Given the exact data of the dwelling structure, we still have to make some assumptions: Let us assume one damaged apartment and one damaged adjoining building per dwelling and use the observation that out of the 234 residential buildings in the WAL risk zone, about one third of the 132 residential buildings with an oil heating system are not sufficiently protected against leakage and will cause oil/static damage. Let us further plug in the relevant figures (actually observed) of average water level at 2.1 m in all cellars, 0.4 m in all ground floors and 2.1 m in all adjoining buildings, together with an average ground floor surface of 50 square meters, a cellar surface of about 70 square meters and an average surface in an adjoining building of 30 square meters. Such input data can generally be obtained ex ante. On this basis, we would have predicted flood damage of € 14.4 million using Eq. (2) and € 14.8 million applying Eq. (1), i.e. only a slight overestimation of the actual damage incurred of € 14.2 million. The damage thus evaluated corresponds to about 19% of the maximum damage potential based on the market value of residential buildings in the WAL risk zones (see Sect. 2). While such a comparison may aid understanding of the numerical and monetary dimensions of the flood event, we did not try to estimate a relative damage function on this basis.

Table 6. Cross-validation results of the final model of Eq. (2).

	Mean absolute error	Root mean squared error (RMSE)	% of data points within the ±1 RMSE band	Theil inequality coefficient
Testing sample set	17 683	22 938	82%	0.17 (covariance proportion: 0.91)
Validation sample set	17 766	23 455	77%	0.16 (covariance proportion: 0.93)

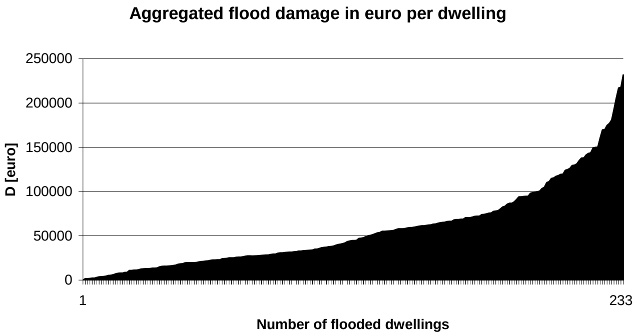

Fig. 6. Damage (D) in € in ascending order. Data source: Amt der NÖ Landesregierung, Abteilung Landwirtschaftsförderungen (2006a).

7 Conclusions

The main aim of the paper was the estimation of absolute flood damage on newly available data (for the flood event 2006) on a dam breach scenario. Since the underlying damage assessment was known, theoretical reasoning, research data, as well as statistical criteria, all contributed to the choice of functional form. Although damage estimation was primarily based on water volume instead of water depth, there was still some variability in the data. However, by separating out oil and static damage from the sample, the variability was reduced and estimates for different building types and damage categories could be generated independently. Taking into account the suggested flood damage curve proposed by Lebensministerium (2008), a function including a constant $S_{\min}$ was chosen, whereby the use of water volumes rather than water depths was found to be preferable. The product of square meters and water depth as interaction variable (i.e. volume) performed statistically much better in the regression than square meters and water depth individually. In addition, when implementing a square root function with respect to Eq. (2), the water-volume-damage function was misspecified (according to general specification tests), leading also to a negative value of $S_{\min}$. In order to obtain a positive value of $S_{\min}$, a square-root function of water volume was not found to be adequate. In addition to theoretical reasoning, i.e., for reasons of interpretation, the lin-lin functional form (Eq. 2) is finally recommended owing to its ability to accelerate damage assessment procedure and its general ease of applicability (taking the logarithm of water depth in Eq. (1) entails estimation problems for values of zero). In addition to testing goodness of fit with respect to sample data, the quality of future prediction of the estimated flood damage curves (Eqs. 1 and 2) was tested via split-half-cross-validation. The flood damage curves (Eqs. 1 and 2) were also applied in "predicting" potential flood damage for the specific dam-breach scenario under investigation. However, compared to natural flood waves in rivers due to heavy rain or snow melt, it needs to be noted that such dam-break events cause buildings to be flooded at the same water depth for a shorter time and carry less total water volume. Thus, although appropriate in the case of a dam-break event, for more general application, the curve proposed in Eq. (2) should be further checked against field data on damage caused by natural waves in rivers. Also the question of the proportion of oil tanks not sufficiently protected against leakages (one third in our sample) should be further investigated given the high damage constant involved. Lebensministerium (2008) estimated flood damage curves for different building floors and gave an example of flood damage of € 31 527 = € 1500+€ 1000·28·$\sqrt{1.15}$ resulting from an estimated flood damage function where 1500 stands for $S_{\min}$ and 28 for the respective coefficient with an assumed water level of 1.15 m. By plugging in the same water level of 1.15 (along with our average ground floor square meters of 51 in Table 3) in our final Eq. (2) we obtain a slightly higher regular damage figure of € 33 988, assuming no oil damage and that water level in the adjoining building and the cellar is zero. Hence, on average there is no evidence of divergence between results derived from our estimated flood damage function and the one proposed by Lebensministerium (2008).

Additionally, our model indicates oil damage amounting to about € 133 537, approximately three times higher than our resulting mean regular damage figure of € 41 039. This is in line with the findings of Müller (2000) for Germany (assuming the mean water level and square meter value for the ground floor, the cellar and the adjoining buildings as indicated in Table 3).

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