Vulnerability of buildings to storm damage in Germany

Patrick Heneka[a,b], Bodo Ruck [a]

[a] *Institute for Hydromechanics, University of Karlsruhe, 76128 Karlsruhe, Germany*
[b] *Center for Disaster Management and Risk Reduction Technology, University of Karlsruhe, 76187 Karlsruhe, Germany*

ABSTRACT: The development of storm damage functions is of importance for damage and risk assessment of extreme storm events. Building damage data of four winter storms in the German state of Baden-Württemberg are analyzed in order to quantify the relationship between gust speed and amount and number of damages. It was found that the incorporation of the local wind climate is necessary to describe storm damage rather than solely dealing with the absolute gust speed. A new damage model is described and calibrated to the available data. In contrast to empirical functions, the new function are based on logical and physical assumptions. Finally, the application in storm damage scenarios and storm risk maps is demonstrated.

KEYWORDS: winter storm, storm damage function, residential buildings, wind climate

1 INTRODUCTION

In Germany, besides inundation events, extratropical cyclones cause most of damage of all natural hazards due to their large spatial extent and high wind speeds. These winter storms mainly develop over the Atlantic Ocean under favorable conditions such as high temperature gradients and strong jet stream wind speeds. Not seldom, multiple countries of Western and Middle Europe are affected. For example, winter storm “Lothar” in 1999 hit large parts of Western Europe and produced economic losses of more than 6 billion €. According to [1], in Germany, winter storms caused more than 27% of the economic and more than 45% of the insured damage of all catastrophic natural events between 1970 and 2004. The estimation of storm damage and risk is therefore of prime importance for disaster managers and insurance industry.

Damage and risk calculation require both the meteorological and the engineering input. In this context, the simulation of vulnerability of the existing building stock to winter storms in Germany is the most challenging task. For the simulation of vulnerability, storm damage functions are used that basically combine meteorological and structural parameters with the consequent damage to structures. While a great variety of damage functions are available for building structures in hurricane prone areas [2], no comprehensive functions exist for Germany. Empiric damage functions like in [3] have the disadvantage that they are not necessarily valid for higher wind speeds than used for calibration. Moreover, the commonly used power 3 relationship between wind speed and damage is solely based on empirical evidence and does not have physical background [4]. Other approaches for European buildings, like Dorland’s exponential function [5], have the disadvantage that absolute monetary values are calculated which can not be adapted to other regions.

2 WINTER STORM DAMAGE IN GERMANY

2.1 *Overview*

Typical winter storms in Germany are characterized by wind speeds of 30 to 50 m/s in lowlands and up to 70m/s in mountainous terrain. Duration of extreme winds reaches from several hours up to half a day. Large winter storms affect areas of some 1000km in length and more than 500km in width. Destruction is mainly caused by high wind speeds, but also by extensive precipitation, inundation and – at the North Sea – storm surge.

In contrast to tropical cyclone or tornado damage, winter storms cause only light damage to buildings. Average storm damage amounts to about 1,500€ for private residential buildings and 4,000€ for commercially used buildings. The huge total losses have their origin in the large number of affected buildings that easily exceed several 100,000.

2.2 *Relationship between damage and meteorological parameters*

For four winter storms, an extensive set of damage data of postal code zones in the German state of Baden-Württemberg is available (Tab 1). Situated in the South-West of Germany, Baden-Württemberg is characterized by topographically complex terrain dominated by the river Rhine valley and the low range mountains of the Black Forest. The damage ratio DR (ratio of amount of building damage to total replacement costs) as well as the claim ratio CR (ratio of damaged buildings to total number of buildings) are available for each of the 1160 postal code zones and storm.

Table 1. Overview of damage data of the investigated storm events

Name of storm Date	Sturm 1986 20.10.1986	Wiebke 28.2.-1.3.1990	Lore 28.1.1994	Lothar 26.12.1999
Amount of damage* [€]	4.7 Mil.	50 Mil	24 Mil.	304 Mil.
Number of buildings	3,083	34,270	17,337	197,520
Average gust speed	27.9m/s	34.2m/s	31.8m/s	38.5m/s

(*residential buildings only)

For the wind speed information, a numerical model approach is needed as no more than 15 weather stations of the German weather service (DWD) are available within the state area. A physical based spatial interpolation technique is applied that used these stations as sampling points. For the numerical wind field simulations, the Karlsruher Atmospheric Mesoscale Model (KAMM) of the Institute of Meteorology and Climate Research of the University of Karlsruhe is used. The model computes the maximum 10 minute wind speeds at 10m above the ground level in a raster of 1km by 1km. Model inputs are meteorological reanalysis data of the European Centre for Medium-Range Weather Forecasts (ECMWF) and the wind speed information of the DWD stations at the moment of the highest storm intensity. Gust factors for different land use classes are used in order to calculate the corresponding gust speeds. A detailed description of the approach is described in [6]. Finally, using a GIS, wind speed information for built-up areas of every postal code zone is extracted. The average of these gust speeds of all zones in the state is also given in Table 1.

In Figure 1, damage and claim ratios of the postal code zones are plotted against the maximum gust speeds. Every point represents one postal code zone. The floating mean and limits of the standard deviations are additionally displayed. A trend to higher damage and claim ratios with increasing gust speeds is obvious, although the single points scatter over a large area. In other words, at the same gust speed calculated by the model, a large variety of different damage is observed. Thus, wind speed as only parameter does not explain damage satisfactorily.

Assuming that the building's vulnerability is proportional to a characteristic wind speed within the area, – due to a traditional adoption of construction to wind climate[1] – damage and claim ratio are plotted against the relative gust speed in Figure 2. The relative gust speed $v_{gust}/v_{p=0.02}$ is the ratio of gust speed and a wind speed with a common probability of exceedance. Here, for every postal code zone, the 50 year gust speed with the annual probability of exceedance of 2% is used as characteristic wind climate. Also others are possible, e.g. [4] are using the 98^{th} percentile of wind speed time series. The 50 year gust speed is calculated based on the annual strongest storms from 1971 to 2000 in a 1km x 1km resolution [6]. In Figure 2, a much clearer trend towards higher damage and claim ratios with increasing relative gust speeds is observed. Moreover, the scatter is less than in Figure 1. As a result, the exceedance of a local wind climate and not the absolute wind speed is decisive for the amount of damage and the number of damaged buildings within a postal code zone.

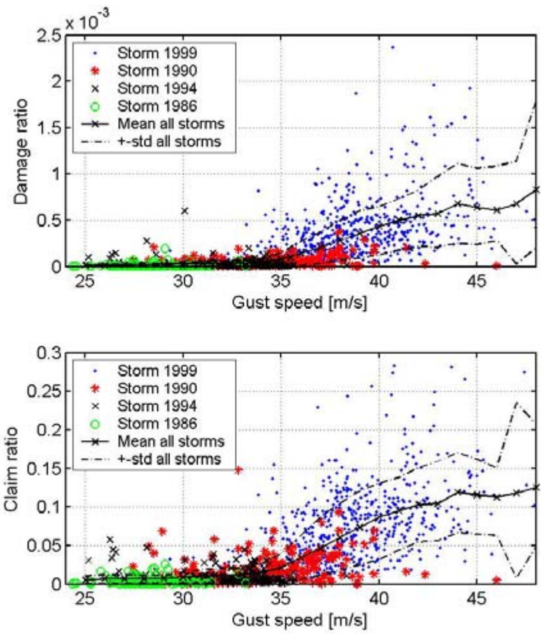

Figure 1: Damage and claim ratio of postal code zones plotted against maximum gust speeds.

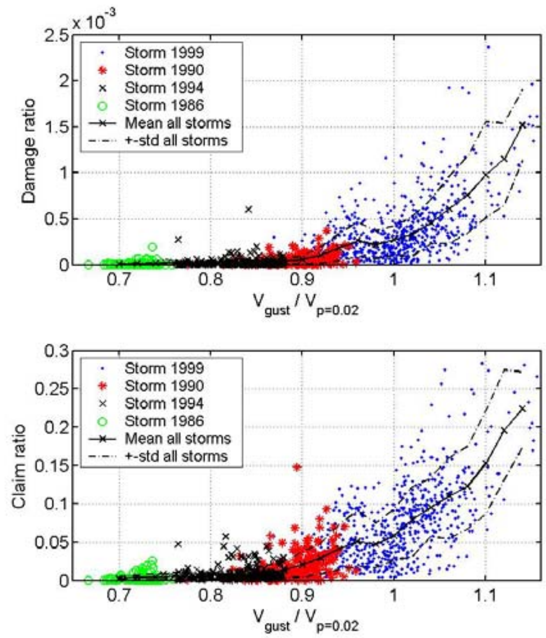

Figure 2: Damage and claim ratios of postal code zones plotted against relative gust speeds.

In order to obtain more arguments for this observation, damage is analyzed with respect to the height above sea level (a.s.l.) of the postal code zones. In general, higher elevation implies higher wind climate. In Baden-Württemberg, elevations of postal code zones cover heights a.s.l. from 100m to 1000m. In Figure 3, the average of the gust speeds for every storm event is increasing with increasing heights. If vulnerability was dependent solely on gust speed, one would also expect higher damage and claim ratios in larger heights. The two diagrams on the right side show the damage and claim ratios plotted against the height above sea level. Here, the ratios are not increasing with height, thus, the absolute gust speed is not suitable to describe storm damage. In contrast, the relative gust speed is not necessarily increasing with height. For example, winter

[1] In the German standard DIN 1055, wind load on structures, the construction wind speed for the majority of existing residential buildings was only dependent on the height of the building, not on the wind climate. This changed in 2005 by introducing a wind zone map.

storm *Lothar* 1999 was relatively strong at heights below 400*m* in comparison to wind climate. The diagram shows, that damage and claim ratios are also above average in these heights, less damage was observed at postal code zones with higher elevation. Even though this trend is less pronounced for the other investigated storms, it can be clearly stated, as a result, that wind climate plays an important role for the occurrence of storm damage.

Additionally, the influence of topography on storm damage was investigated. It was found by the author [7], that the local orographic situation (in less than 500m surrounding) influences damage occurrence in such a way that in deep valleys less damage and on exposed sites more damage was observed. In contrast, the surrounding land use of the postal code zones – like open or forested terrain – could not be definitely set in relationship with the amount and number of damage. Other parameters like building structure, age, storm duration could not be investigated due to the lack of suitable data.

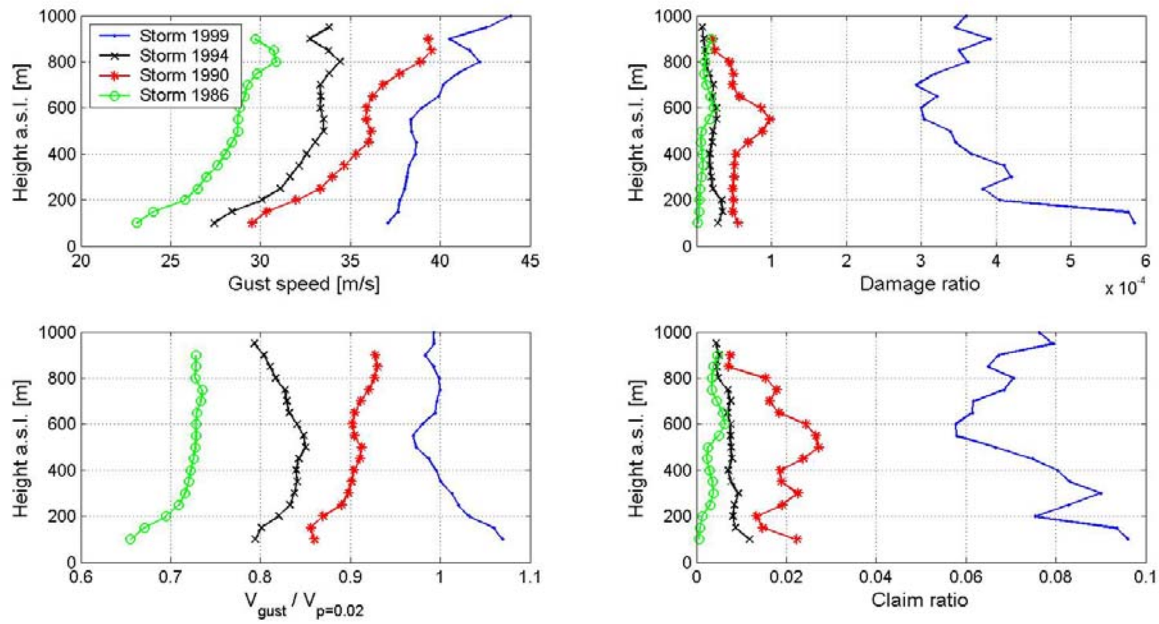

Figure 3: Absolute, relative gust speed, damage and claim ratios plotted against height a.s.l. of postal code zones.

3 MODELING VULNERABILITY

A new storm damage model is proposed that has the following advantages: 1.) The model framework is exact; assumptions are based on logical and physical evidences. 2.) The assumptions can be freely modified and adapted if better ones are available. 3.) The model is therefore valid also for stronger storms than the ones used for calibration. A similar approach was chosen by [8].

3.1 *Storm damage function*

The storm damage model is based on the following hypothesis: Let v be the maximum wind speed during a storm event. A structure suffers damage, if v is higher than the critical wind speed v_{crit}. The latter is the wind speed at which damage to a structure occurs for the first time. Maximum damage is reached at wind speeds higher than the structure's total wind speed v_{tot}. At wind speeds between these limits, damage can be expressed by a function g(v). For every single building, the damage ratio G is therefore written in sections as

$$G(v) = \begin{cases} 0, & v < v_{crit} \\ g(v), & v_{crit} \leq v < v_{tot} \\ 1, & v \geq v_{tot} \end{cases} \tag{1}$$

For reasons of simplicity, the damage propagation function g(v) is supposed to be proportional to the wind speed with a power coefficient (Equation 2). Here, for $\alpha = 2$, damage would be proportional to the force of the wind flow. For $\alpha = 3$, it would be proportional to the energy of the wind flow. In general, any more sophisticated function g(v) could be used when further information on damage propagation is available.

$$g(v) = \left(\frac{v - v_{crit}}{v_{tot} - v_{crit}} \right)^{\alpha} \tag{2}$$

Due to variable building quality and maintenance, the critical wind speeds of buildings within a number of buildings will not be equal. They will rather be distributed in a way. In our case, it is assumed that v_{crit} follows a normal distribution $f(v_{crit})$ with a mean critical wind speed μ_{crit} and a standard deviation σ_{crit} – in contrast to [8] where a triangular distribution functions was used to estimate this variability. At a wind speed v, all those buildings are damage whose critical wind speed is less than v. Thus, the claim ratio is calculated to

$$CR(v) = \int_{-\infty}^{v} f(v_{crit}) dv_{crit} \tag{3}$$

which equals the cumulative density function (CDF) of $f(v_{crit})$. In this distribution, μ_{crit} corresponds to the gust wind speed at which 50% of the buildings in the population are damaged. The two parameters of the distribution function have to be adapted to fit the available damage data. The total wind speeds v_{tot} are also distributed, for simplicity we assume a distribution correlated to v_{crit} in such a way that $v_{tot}-v_{crit}=\Delta v$ is constant for every building. Further on, assuming the same damage propagation characteristics and an average value of the maximum damage for all buildings, the damage ratio DR for an amount of buildings as a function of the maximum gust wind speed v can be calculated to

$$DR(v) = \int_{-\infty}^{v} f(v_{crit})\, G(v)\, dv_{crit} \tag{4}$$

Here, the parameter Δv has to be adapted to fit the damage data, assuming that α in Eq. (2) is fixed. In order to obtain the total number of damaged buildings and the damage sum, CR and DR have to be multiplied by the total number of buildings and the total value, respectively. The total value of private residential buildings in German communities is calculated in [9] and equals the replacement costs with reference to the year 2000.

Again, the damage propagation function g(v) and distribution function f chosen for v_{crit} are first approaches and, hence, subject to inaccuracies. However, within this mathematical framework, any function or distribution can be used.

3.2 *Calibration*

Within the above developed framework, two model versions with different assumptions are calibrated and compared: Damage model 1 calculates storm damage assuming that damage of an area is only dependent on the maximum gust speed. This is how most published models work. In contrast, damage model 2 is based on the assumption that damage is rather dependent on the

relative wind speed $v/v_{p=0.02}$.Thus, the model is also dependent on the local 50 year gust speed in the area. These different models follow the representation in Figures 2 and 3.
The models were calibrated with damage data of the 4 investigated storm events. The parameters of the distribution function $f(v_{crit})$, μ_{crit} and σ_{crit} and the damage propagation function $g(v)$, Δv were fitted by a least square method of the total damage of the storm events. The power coefficient α was set to 2, as any other value was leading to large errors at high wind speeds. The coefficients found are listed in Table 1. The values for μ_{crit} are in good agreement with damage functions from [3] and [10].

Table 1. Parameters for the storm damage function

	μ_{crit}	σ_{crit}	Δv	α
Damage model 1	50.4m/s	7.8m/s	78m/s	2
Damage model 2	1.305	0.195	2.08	2

The storm damage of the investigated storm events was calculated and compared with the available damage data. It turned out that the error in total damage of state of Baden-Württemberg was of more than 50% for damage model 1 and less than 20% for damage model 2. The most damaging event *Lothar* was calculated best with an error of the total damage of about 10%.
Another important feature in order to check the quality of the models is the spatial distribution of damage. The calculated correlation coefficients between modeled and observed damage data of the postal code zones for the 4 storm events are listed in Table 2. Here, damage model 2 shows a much higher accordance with the observed data as damage model 1. The highest coefficients are those of winter storm *Lothar* which can be explained by the larger amount of damage and consequently minor random effects. The stronger the intensity of a storm is, the better the spatial damage distribution is calculated.

Table 2. Correlation coefficients between modeled and observed storm damage

Name of storm Date	Sturm 1986 20.10.1986	Wiebke 28.2.-1.3.1990	Lore 28.1.1994	Lothar 26.12.1999
Damage model 1				
Amount of damage	0.190	0.299	0.134	0.627
Number of buildings	0.221	0.402	0.238	0.763
Damage model 2				
Amount of damage	0.257	0.582	0.345	0.868
Number of buildings	0.281	0.653	0.478	0.864

Figures 4 and 5 show the comparison of the two developed models to known damage models of [3,11,10,12]. Damage model 2 is calculated with two different 50 year gust speeds, 35 and 45m/s, in order to illustrate the range of the model. For gust speeds higher than 50m/s, both models lay exactly in the range of the model developed by [10]. At lower gust speeds, the damage models predict much smaller damage than the others. A possible reason is that often not the mean of the model output is used than rather the envelope in order to account for the complete range of damages.

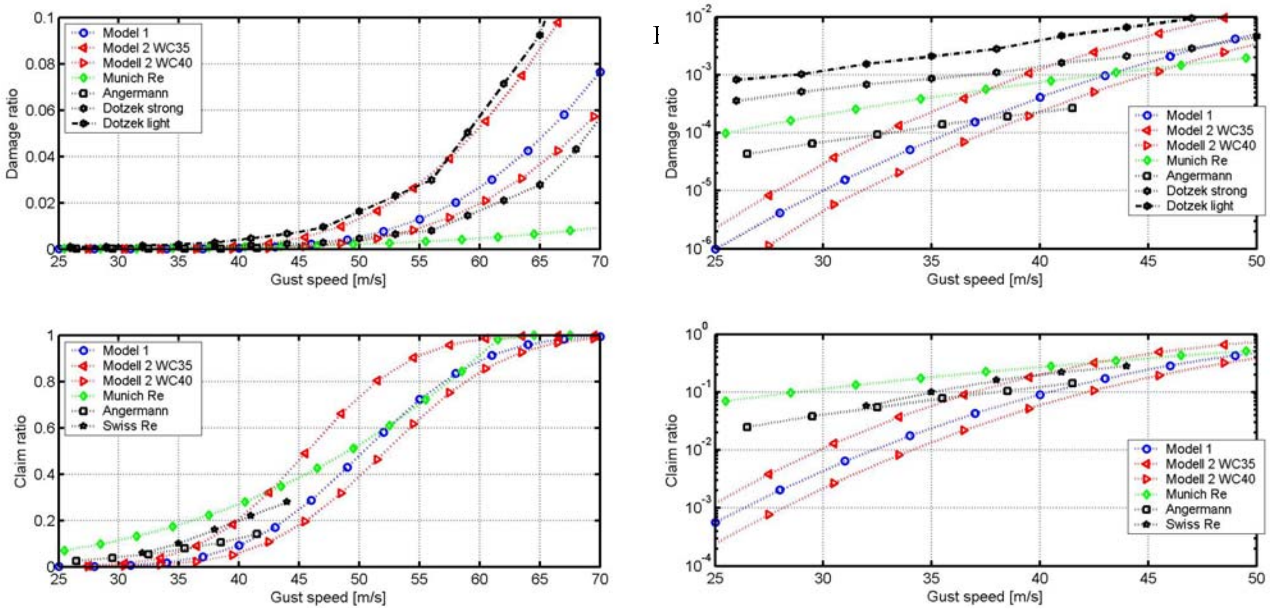

Figure 4. Storm damage models

4 APPLICATION

The developed storm damage functions are used for the assessment of storm risk in Germany. Therefore, information about storm hazard, vulnerability and value are available for every single municipality in Germany. Storm hazard denotes the wind speeds that are exceeded at a certain level of probability during a period of time. Its calculation is performed with the method of the annual strongest storm between 1971 and 2000. The Gumbel function is used as extreme value distribution function. By combining hazard with storm damage functions and the total buildings value, storm damage risk is calculated for every municipality.

In average, a 50 year wind speed damages 6% of all buildings in a municipality and causes damages of 0.25% of the total reconstruction costs of all buildings (compare Figure 2 at $v_{gust}/v_{p=0.02} = 1$). The result is remarkable, as the German building code DIN 1055 part 4 requires construction wind loads of exactly this level of probability. As further result, the average annual loss in the state of Baden-Württemberg is estimated to 13 Mil. € for all events up to a probability level of p=0,002 (equal to a 500 year mean recurrence interval). This equals a damage of 5€ per residential building and year.

Additionally, damage of storm scenarios can be estimated with the developed storm damage functions. As an example, in Figure 6, the comparison between simulated and observed damage of winter storm *Lothar* is shown. Also, the calculation of fictitious, but possible scenarios can be done, which clarifies the possible impact of winter storms in Germany.

5 CONCLUSION

The developed damage model allows the estimation of storm damage to residential buildings with the knowledge of the maximum gust speeds and the local wind climate within the area of postal code zones. The model was calibrated to damage data of the German state of Baden-Württemberg. An ongoing task is the validation of the model with damage data of other states, preferably of the north of Germany as wind climate is about 5-10m/s higher than in the south.

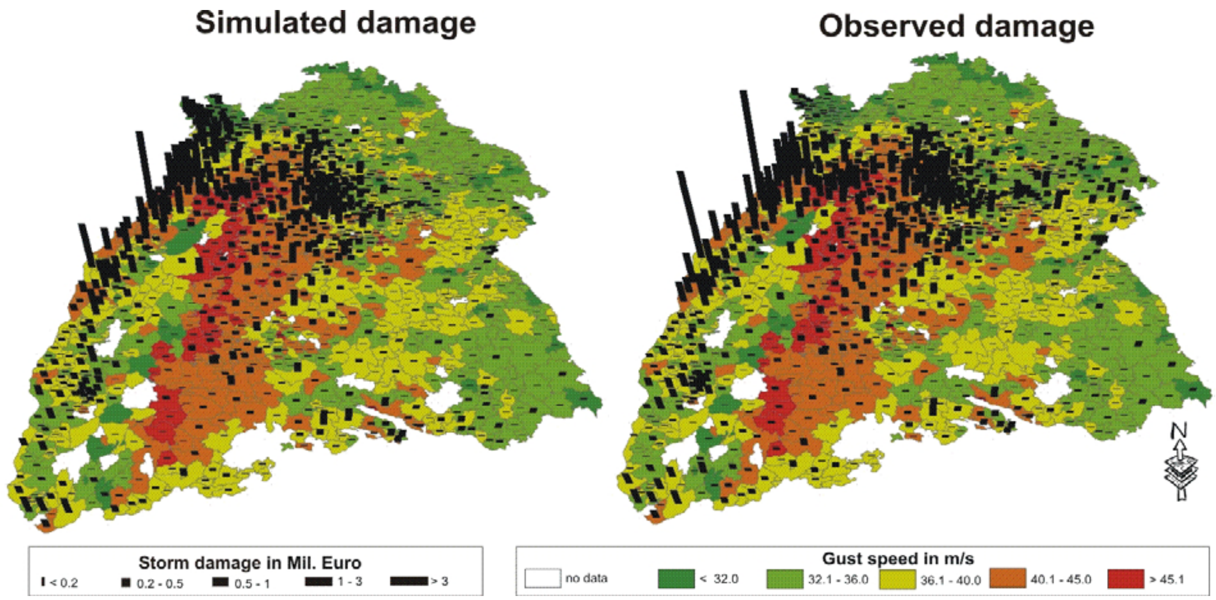

Figure 6: Comparison between simulated and observed damage distribution of winter storm *Lothar* in 1999.

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