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New insights into flood warning reception and emergency response by affected parties

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Abstract. Flood damage can be mitigated if the parties at risk are reached by flood warnings and if they know how to react appropriately. To gain more knowledge about warning reception and emergency response of private households and companies, surveys were undertaken after the August 2002 and the June 2013 floods in Germany. Despite pronounced regional differences, the results show a clear overall picture: in 2002, early warnings did not work well; e.g. many households (27 %) and companies (45 %) stated that they had not received any flood warnings. Additionally, the preparedness of private households and companies was low in 2002, mainly due to a lack of flood experience. After the 2002 flood, many initiatives were launched and investments undertaken to improve flood risk management, including early warnings and an emergency response in Germany. In 2013, only a small share of the affected households (5 %) and companies (3 %) were not reached by any warnings. Additionally, private households and companies were better prepared. For instance, the share of companies which have an emergency plan in place has increased from 10 % in 2002 to 34 % in 2013. However, there is still room for improvement, which needs to be triggered mainly by effective risk and emergency communication. The challenge is to continuously maintain and advance an integrated early warning and emergency response system even without the occurrence of extreme floods.

1 Introduction

In recent years, floods have caused high economic damage in European countries. In Germany, for instance, the extreme flood event of August 2002 caused 21 fatalities and financial losses of EUR 11 600 million (Thieken et al., 2006). In June 2013, large-scale flooding caused 14 fatalities and financial losses of around EUR 8000 million in Germany alone (Thieken et al., 2016a). The economic damage from floods has been increasing over the last decades, mostly due to increasing exposure driven by societal factors like augmented standard of living, wealth and population density (Barredo, 2009). This trend is likely to continue (IPCC, 2012; Jongman et al., 2014). For example, a 20-fold increase is expected for the economic flood risk by the year 2080 in England and Wales if flood risk management is not improved significantly (Hall et al., 2005). In continental Europe, flood losses could more than double by 2050 due to climate change and socioeconomic development (Jongman et al., 2014).

The recent damaging events and anticipated developments have triggered calls for better risk reduction strategies. In fact, flood risk management has become an important policy field in Europe. To ensure a consistent approach for better assessment and management of flood risks in the whole of the European Union, the European Floods Directive (EC, 2007; 2007/60/EC) came into effect in 2007. It requires that member states conduct quantitative hazard and risk analyses and develop risk management plans that are expected to address a wide range of measures beyond structural flood defences. Hegger et al. (2014) distinguish five flood risk reduction strategies: (1) loss prevention by an adapted use of flood-prone areas; (2) risk mitigation by flood-adapted de-

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sign and use of buildings; (3) flood defence through structural protection measures; (4) preparedness for response, e.g. using flood warnings and adequate responsive behaviour; and (5) risk transfer mechanisms such as flood insurance to compensate for flood losses. The Floods Directive reflects that flood risk management has shifted from flood protection to the more comprehensive approach of integrated flood risk management (Merz et al., 2010; Bubeck et al., 2017).

While integrated flood risk management seems to be a recent development, it has to be emphasized that – besides structural measures – flood warning and emergency response have a long history. For example, a first transboundary system for the dissemination of alerts along the rivers was established in central Germany in 1889 (Deutsch and Pörtge, 2001). Nevertheless, recent events such as the flood of 2002 revealed deficiencies in early warning as well as a huge lack of general risk awareness, communication and preparedness of at-risk households and companies (DKKV, 2003). Therefore, amendments of the warning and response system as well as campaigns to improve risk communication and preparedness were requested and have been implemented since then (Thieken et al., 2016b).

Although early warning and emergency response typically aim to protect human life as a first priority, their potential to significantly reduce economic damage has been recognized for a long time (e.g. Handmer et al., 1988; Thieken et al., 2005a; Meyer et al., 2012; Molinari et al., 2013). However, empirical studies on the effectiveness of early warning and emergency response are rare. One early exception is provided for the flood in Lismore (Australia) in 1974: with a lead time of about 12 h, damage in the residential sector was only 50 %, and in the commercial sector it was only 24 % of the economic damage expected without emergency measures (Smith, 1981). Another example is early warning and response to flash floods in the city of Sondrio, Italy: there it is estimated that responsive action led to a damage reduction of about 10–25 % (Molinari et al., 2013).

Important factors influencing the effectiveness of emergency response in reducing damage are the lead time, the flood intensity and the ability of civil protection and affected parties to undertake emergency measures effectively (Handmer et al., 1988; Penning-Rowsell and Green, 2000; Kreibich et al., 2007a; Molinari and Handmer, 2011; Molinari et al., 2013; Mross et al., 2016). The longer the lead time, the longer the time for undertaking emergency measures. For shallow water levels, damage can be reduced easily by sealing the affected building or by moving contents higher, e.g. onto shelves or higher storeys (Rözer et al., 2016). If water levels are higher than expected, water barriers will be overtopped and the ingress of water can often not be prevented. This is of course a question of how the flood hazard was assessed for the property at risk and how the property-level protection was designed.

The ability to undertake effective emergency measures on the property level is again dependent on different factors, e.g. on recent flood experience, preparedness and availability of emergency plans (Thieken et al., 2007; Kreibich et al., 2007b; Chinh et al., 2016; Morss et al., 2016). People who have witnessed a flood recently tend to be better prepared and tend to have a better idea of what to do when a warning reaches them (Wind et al., 1999; Yeo, 2002; Kienzler et al., 2015). However, it should be noted that first response behaviour is not directed towards loss reduction but towards cross-checking the warning by searching for further confirmative information (Creutin et al., 2009 cited by Parker and Priest, 2012). After that, protective action is organized before it is undertaken. To keep these first two steps as brief as possible, trust in the responsible early-warning institution, the existence of an emergency plan as well as the understandability and the information content of the warning are essential (Kreibich et al., 2007b; Parker and Priest, 2012; Morss et al., 2016). First loss-reducing measures include evacuation, safeguarding documents and valuables and moving vehicles to higher ground. Subsequently, moveable household items are put upstairs (Parker and Priest, 2012). Although some measures sound rather simple, Morss et al. (2016) highlight that the decision process on what to do in the real flood situation is rather complex. To support decisions, it is increasingly discussed to supplement warning information with information about potential flood impacts (e.g. Coughlan de Perez et al., 2015; Dottori et al., 2017).

Despite its importance, not much is known about flood warning reception and emergency response from the perspective of affected parties. Thus, the objective of this comparative study is to gain more knowledge on how and when households and companies received flood warnings and how they responded in 2002 and 2013. Although the flood of 2013 differed from the 2002 event in its flood characteristics (Schröter et al., 2015; Thieken et al., 2016b), the affected area was comparable (see Sect. 2). Hence, it provides the opportunity to evaluate the improvements in flood warning reception and emergency response by affected parties. To better understand the flood impacts, the next section briefly describes the two events. As background information, Sect. 3 summarizes the development of flood warning and response in Germany, in general, and in the most affected federal states (*Bundesländer*), i.e. in Bavaria, Saxony and Saxony-Anhalt, in particular. In Sect. 4 the empirical data acquisition is described. Results are presented and discussed in Sect. 5, in general, and separated for Bavaria, Saxony and Saxony-Anhalt. Conclusions are drawn in the last section.

2 Event description and study area

In August 2002, flooding occurred in the Elbe and Danube catchments, mainly in the federal states of Saxony, Saxony-Anhalt and Bavaria. The city of Dresden on the Elbe River, the Elbe tributaries in the Ore Mountains (*Erzgebirge*) and the Regen River, a left-bank tributary of the Danube were

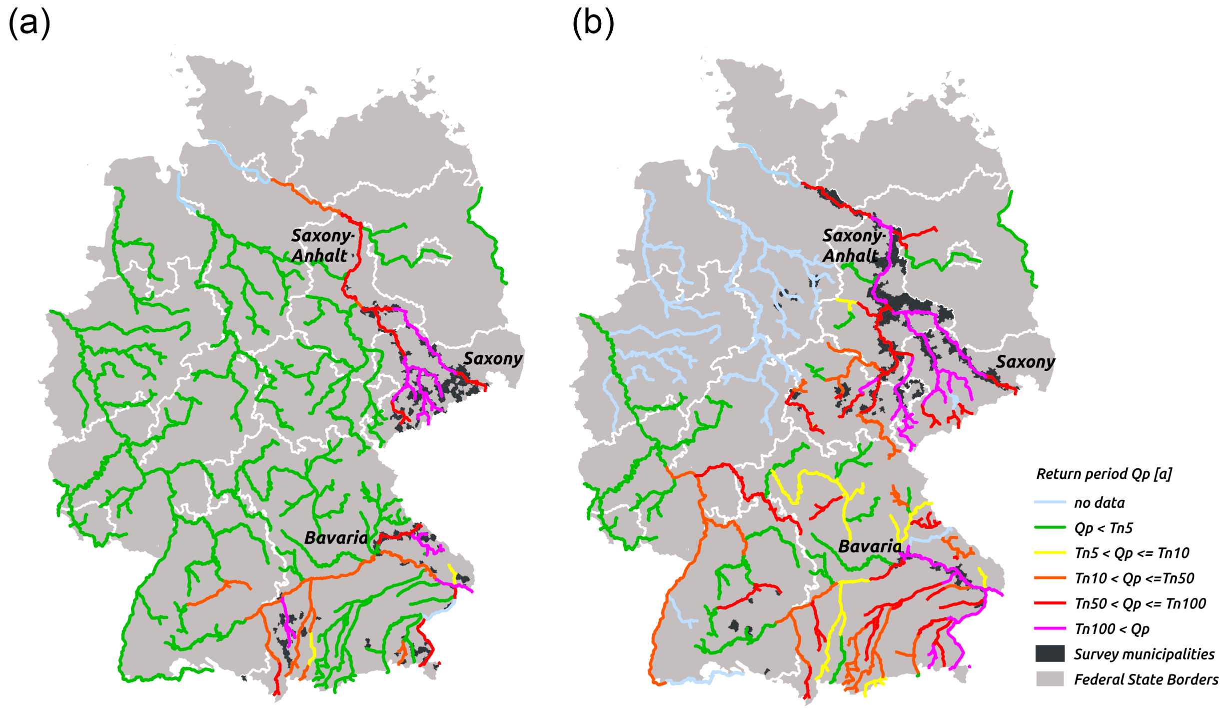

Figure 1. Overview of municipalities where surveys were undertaken after the 2002 **(a)** and 2013 **(b)** flood events. Additionally visualized are return periods of peak discharges (adapted from Schröter et al., 2015).

particularly strongly affected (Ulbrich et al., 2003; IKSE, 2004). Along some Elbe tributaries flood peak discharges exceeded the 500-year return period (IKSE, 2004; Engel, 2004); see Fig. 1. Along the Elbe River return periods varied between 150 years at Dresden (Upper Elbe) and 25 years at the Lower Elbe upstream of Hamburg. At the Regen River return periods of 100 to 300 years occurred (Ulbrich et al., 2003).

The occurrence of severe floods in summer in central Europe is often coupled with large-scale weather patterns producing widespread rainfall (Bárdossy and Filiz, 2005; Petrow et al., 2009). The flood in August 2002 was caused by a Genoa Cyclone Type Vb weather system which moved warm and moist air masses of Mediterranean origin in an arc towards northern/eastern Europe resulting in heavy precipitation. In this process the largest rain amounts, which often exceeded 100 mm within 72 h, were observed in eastern Germany. Similar amounts were also recorded in the Bavarian and Bohemian forests as well as along the Alpine foothills. A record-breaking amount of daily precipitation was measured in Germany; i.e. 312 mm within 24 h was reported for 12–13 August 2002 at Zinnwald-Georgenfeld in the Ore Mountains (Ulbrich et al., 2003). This extremely intense precipitation in the Ore Mountains resulted in an immediate runoff response producing flash floods, for instance at the rivers Mulde, Weißeritz and Schwarze Elster with peak discharges observed on 13 August 2002, that formed within only a few hours. These flash floods led to a critical isolation of valleys and municipalities in the Ore Mountains and caught those affected in the middle of the night (DKKV, 2015).

During the August 2002 flood numerous dyke failures occurred, affecting areas where people believed to be safe due to technical flood protection measures in place (Kuhlicke, 2015). In Saxony, 131 dyke breaches or overtoppings occurred, 16 along the Elbe River and 115 in the Mulde catchment. The flood caused 21 fatalities and 108 people were injured; in total, 330 000 people in eight federal states in Germany were affected (EM-Dat, 2015). Emergency response evacuated 35 000 people in the city of Dresden and 60 000 people in the federal state of Saxony-Anhalt (DKKV, 2015). The overall financial loss amounted to EUR 11 600 million (Thieken et al., 2006). Before August 2002, the last severe flood in the Elbe river occurred almost 50 years ago in 1954 (Fügner, 2003; Pohl, 2004). Hence, flood awareness was comparatively low in Saxony and Saxony-Anhalt. This situation was different in the Danube catchment, where flooding had occurred only a few years before in December 1993 and was particularly severe in May 1999, which was reflected in people's awareness and preparedness (Thieken et al., 2007).

In June 2013, large-scale flooding affected almost all main river basins in Germany (Merz et al., 2014; Schröter et al., 2015). Particularly severe flooding occurred along the Elbe River and its tributaries Saale and Mulde in the federal states of Saxony, Thuringia and Saxony-Anhalt and along the Danube River in the federal state of Bavaria. Return periods of peak discharge exceeded 100 years at many gauges along the Elbe River from Dresden to Lenzen as well as in the Mulde and Saale catchments; see Fig. 1. Along a reach of 350 km along the Elbe River between Coswig and the weir at Geesthacht, as well as along the Saale river, record-breaking water levels were registered (Merz et al., 2014; BfG, 2014). In Passau, the highest water level since 1501 was observed due to the superposition of the flood waves from the Inn and Danube rivers (Blöschl et al., 2013).

In May 2013, a quasi-stationary upper-level trough over central Europe triggered several surface lows which on the eastern side advected warm and humid air masses from south-eastern Europe (Grams et al., 2014) northwards and curved into Germany and Austria (Schröter et al., 2015). The intense and widespread precipitation that triggered the June 2013 flood occurred at the end of May and beginning of June. This heavy rainfall was produced by a cut-off low that moved slowly with its centre from France (29 May) over northern Italy (30 May) to eastern Europe (1 June). The most intense precipitation occurred in the Danube catchment in the alpine areas of southern Bavaria and northern Austria. For example, at the gauging station Aschau-Stein of the German Weather Service in the Chiemgau Alps a rainfall total of 346 mm within 72 h was registered (Schröter et al., 2015). This spatially extended, but not extraordinarily high, precipitation in combination with high antecedent catchment wetness was the main driver of the June 2013 flood (Merz et al., 2014; Schröter et al., 2015). Accordingly, the development of the June 2013 flood was less dynamic than the August 2002 flood but more widespread. The 2013 flood developed over several days. The extreme water level in Passau occurred on 3 June (Blöschl et al., 2013; BfG, 2014). In the Elbe River an elongated flood wave developed with peak discharges occurring on 6 June in Dresden and 11 June in Geesthacht (BfG, 2014), carrying huge volumes of water with unusual simultaneous discharge contributions from the Elbe, Mulde and Saale catchments (Conradt et al., 2013).

In June 2013 fewer dyke failures occurred than in August 2002, namely five breaches in the Saxon part of the river Elbe and 24 failures along the river Mulde (DKKV, 2015). Still, three breaches of dramatic dimensions occurred: near Deggendorf at the Danube River, near Groß Rosenburg at the confluence of Saale and Elbe rivers and near Fischbeck at the Elbe River (Merz et al., 2014). The flood caused 14 fatalities, 128 people were injured, and in total 600 000 people were affected in 12 federal states in Germany (EM-Dat, 2015; Thieken et al., 2016a). Emergency response services had to provide for more than 80 000 evacuations. Major activities were required on 10 June 2013 mostly in Saxony-Anhalt with 40 000 evacuations as entire villages and urban districts were affected (DKKV, 2015). However, in 2013, disaster response organizations had fewer life-threatening situations to cope with and affected people had more time for emergency measures. The overall financial loss estimates sum up to EUR 8000 million (Thieken et al., 2016a).

After 2002, floods occurred in 2005, 2006, 2010 and 2011 in the Danube and Elbe catchments (Kienzler et al., 2015). Thus, due to this increased flood experience and intensive risk communication campaigns after 2002, residents and companies were highly aware of the flood risk and better prepared, as already demonstrated for the smaller flood of 2006 (Kreibich et al., 2011). We therefore hypothesize that the warning reception and emergency response were more efficient in 2013.

3 Background: flood warning in Germany

A successful flood warning system consists of several interacting components: (1) continuous monitoring and forecasting of weather patterns, particularly precipitation, and water levels; (2) detection of potentially hazardous situations; (3) definition and implementation of rules on when, how and whom to warn in case of rising flood water levels and what to communicate in order to activate organizations in charge of civil protection as well as potentially affected people; and (4) an adequate and effective response to the unfolding flood situation (e.g. Parker et al., 1994; Parker and Priest, 2012). Hence, a flood warning system is more adequately addressed as a flood-forecasting, warning and response system (FFWRS; Parker and Priest, 2012). In a FFWRS, several organizations have to collaborate and information has to be communicated, disseminated and interpreted correctly along a chain of different stakeholders, including the general public, which opens the door for many pitfalls that reduce the system's overall efficiency. Consequently, redundancies are seen as an important principle at all levels (Parker and Priest, 2012). The FFWRS's different components have to be developed, maintained, institutionalized and aligned to ensure a proper functioning of the whole system. If one element fails, the whole system is very likely to fail. So, the interaction between the single components needs special attention.

In the 1990s, many European FFWRS often underperformed because warning dissemination and response were unsatisfactory (Parker and Fordham, 1996). Since then, research on and implementation of FFWRS have been considerably augmented. A survey conducted by the European Environment Agency revealed that 70 % of European countries have planned or implemented improved flood information and forecasting systems (EEA, 2007). However, investments in the development of meteorological and flood-forecasting systems were often undertaken without adequately accounting for the communication and dissemination of warnings (Grünewald et al., 2001). Considering the human factors and social issues of communication and behaviour involved in a FFWRS, improvements of data and forecasting models do not necessarily lead to reduced losses (Parker and Priest, 2012). Another recent review confirms these evaluations and concludes that "despite substantial technical progress, major challenges remain to achieve the potential benefits of flood early-warning systems, in particular in communicating risk information and early warnings to emergency services and the population at risk and consequently trigger response actions" (Cools et al., 2016: p. 117). It is therefore recommended to tailor FFWRS to the available resources in order to run and maintain models and to integrate (local) knowledge of the potentially affected parties, which increases the adequacy and understanding of issued warning levels (Cools et al., 2016). Trust is seen as an important asset for partnerships along the warning chain as well as for the acceptance of warnings and the response by the general public (Parker and Priest, 2012; Cools et al., 2016; Morss et al., 2016). As background information, this section summarizes how the FFWRS is organized in Germany, how it performed in 2002 and 2013 and what changes were implemented between these two events.

In Germany, the meteorological service (Deutscher Wetterdienst – DWD) is a federal authority under the Federal Ministry of Transport and Digital Infrastructure. By law, DWD is responsible for weather monitoring and forecasting as well as for detecting extreme weather situations across the whole country and issuing appropriate warnings when necessary. Extreme weather situations are, however, restricted to meteorological phenomena such as heavy rainfall. Consequently, additional services are needed for flood forecasting and warning. All water issues, as well as civil protection and emergency management, are the responsibility of the federal states (*Bundesländer*). Consequently, the organization of flood forecasting and warning, as well as the organization of the civil protection, differs throughout Germany and further challenges the functioning of a FFWRS.

In August 2002, a preliminary warning of a rainstorm was issued on 11 August 2002 in the early afternoon by DWD. This was updated to a rainstorm warning by midnight. Further updated warnings were issued from 12 to 14 August 2002. However, a substantial increase in run-off already occurred on 12 August 2002. Particularly in small catchments of less than 300 km^2 where flood forecasting heavily depends on prompt and precise precipitation forecasts and a reliable rainfall run-off model, a lot of warnings were assessed as having arrived too late. In addition, warnings were too imprecise, since the expected rainfall amount was underestimated (see von Kirchbach et al., 2002 and DKKV, 2003 for further details).

With regard to hydrology, it has to be acknowledged that there were more than 200 flood alert and forecasting gauges in the catchment of the river Elbe in 2002 (IKSE, 2001). However, during the flood many gauges, particularly on the Elbe tributaries, failed due to severe inundation or power black-outs. At some places forecasts were issued when the actual run-off had already exceeded the forecast levels. At others, e.g. along the river Mulde, forecasts from different centres were not consistent (von Kirchbach et al., 2002). In 2002, the flood-forecasting model for the Elbe River was based on a regression analysis of discharges and used discharges at upstream gauges as input data. Since water levels in 2002 reached heights for which neither the rating curves nor the regression models were defined, the forecasts were erroneous, leading to overestimations of the maximum flood heights of up to 50 cm, which lead to unnecessary stress and emergency measures in some places downstream.

As far as alerts were concerned, some flood reports were delayed at intermediate stations and reached the civil protection agencies too late. An analysis of deployment reports showed that different authorities responsible for civil protection, relief organizations and support units did not cooperate but primarily acted in an organization-oriented and resource-driven way. Altogether, the analysis revealed four structural failings (DKKV, 2003; Thieken et al., 2005b):

- poor relations between different responding organizations,
- dominance of self-orientation and a lack of orientation towards the situation as a whole and to superior protection objectives (manifested by a lack of knowledge about the qualification and equipment of other organizations, missing consideration of complementary equipment or activities),
- weaknesses of the authorities in civil protection to assess knowledge, motivation, capabilities and capacities of the individual organizations, and
- isolation and centralization of the operative–tactical subsystem, making innovations difficult.

In conclusion, integrated early-warning systems from monitoring to the reaction of the affected parties were insufficiently developed in 2002. Maintenance and upgrading of models and systems to the latest technologies, as well as more efforts to provide up-to-date and reliable input data for the forecast models, were hence recommended (DKKV, 2003). Further, communication of warning messages and coordination of response capacities needed to be revised.

By June 2013, progress in the technical systems including the dissemination of warnings was discernible at all levels (DKKV, 2015). The DWD has improved all numerical forecast models; e.g. the European forecast model that can be used 3 days before the actual event has been implemented on a 7 km grid; forecasts are updated every 6 h. The Germany-wide forecast model COSMO-DE has been implemented on a 2.8 km grid and is updated every 3 h, providing a 27 h forecast. Further, uncertainty assessments by ensemble simulations as well as updated and more differentiated warning thresholds were introduced. Warnings are currently disseminated by various media including web-based services. The DWD has teamed up with emergency response units in the districts and (regional) flood-forecasting centres that use precipitation forecasts as one main input for their rainfall run-off models (DKKV, 2015).

With regard to flood warnings, far-reaching cross-departmental and transnational collaboration across the federal states have been achieved. In some federal states, including Saxony and Saxony-Anhalt, flood forecasting and warning were reorganized after 2002 into one forecasting centre following the single-voice principle. In Saxony, the reorganization also included a redefinition of dissemination and communication pathways. Further, feedback loops were established to avoid interruptions of the alerting process (DKKV, 2015). Similarly, Saxony-Anhalt established a flood forecasting centre in 2008. Bavaria holds a central flood monitoring and warning centre that also collects the forecasts from decentralized forecasting units in different catchments. All federal states have established a state-specific web portal on which the general public can access information about the flood situation. In addition, a joint internet portal (http://www.hochwasserzentralen.de) was established by all federal states to allow a country- and basin-wide assessment of the flood situation, which had been impossible back in 2002 (DKKV, 2015). In general, a survey among the upper water authorities revealed that flood forecasting and warning is seen as an essential part of flood risk reduction by 10 out of 12 participating states (DKKV, 2015) and consequently receives considerable attention and resources.

In 2013, precipitation and run-off forecasts were in general precise and were issued well in advance of actual inundations (e.g. DWD, 2013; DKKV, 2015). In some places there were, however, inaccuracies in the rainfall forecasts that propagated to the run-off forecasts. Occasionally, the all-clear signal was given too soon or an overload of the IT systems occurred, so that the exchange of data and its onward transmission were compromised. For instance, Saxony-Anhalt reported difficulties like system breakdowns (DKKV, 2015), which were mainly due to the more severe flood situation in 2013. The middle reaches of the river Elbe were more heavily affected in 2013 than in 2002 and the river Saale was additionally impacted, which was not the case in 2002. The timely and reliable identification of levee breaches and their effects on the flood situation downstream as well as on the inundation of the hinterland was difficult, especially in Bavaria and Saxony-Anhalt (DKKV, 2015; Thieken et al., 2016b). Based on these findings, it has been recommended that rainfall forecasts should be further improved and that rainfall run-off models should be expanded, especially with regard to a common appraisal of uncertainties and inclusion of failures of protective structures. Altogether, a comprehensive communication along the warning chain was largely achieved in 2013, but continuity, redundancy and capacity of the technical systems and staff must be guaranteed to keep this level of performance (Thieken et al., 2016b).

Despite some very challenging situations, the overall emergency management was significantly more effective in 2013 than in 2002. Collaboration within and among different disaster response organizations has clearly benefited from the coordination of the Joint Reporting and Situation Centre (GMLZ) that was established after the 2002 flood. Additionally and from transnational exercises, e.g. the biennial transnational crisis management exercise LÜKEX, which strongly contributed to a high-performance capacity of the emergency response (DKKV, 2015).

4 Surveys and data

Computer-aided telephone interviews (CATI) were conducted with private households and companies which had been affected by the 2002 or 2013 floods in Germany (Table 1). The household survey on the 2002 flood was restricted to the federal states of Saxony, Saxony-Anhalt and Bavaria, and the company survey was restricted to Saxony. The surveys on the 2013 flood were not restricted with respect to federal states. Interviews were undertaken in the whole of the flood-affected area. For all surveys, lists of affected streets were compiled on the basis of information from affected districts or municipalities, flood reports and press releases, as well as with the help of flood masks derived from satellite data (DLR, Center for Satellite Based Crisis information, https://www.zki.dlr.de/). These provided the basis for generating property-specific random samples of households and companies. Property-specific means that only one household or company was interviewed per address. The telephone numbers were generally retrieved from the public telephone directory or the commercial telephone directory (yellow pages). For the survey on the 2002 flood, households and companies from the list of telephone numbers were sampled randomly. For the survey on the 2013 event, a comprehensive survey was conducted, i.e. all the researched telephone numbers were contacted. An impact on the results due to this difference is not expected.

For the surveys of companies, additional effort was undertaken to identify and interview large companies. Flood reports and press releases were analysed and experts were interviewed to find additional large affected companies. After the 2002 flood, large companies were interviewed separately in May 2004 (Table 1). After the 2013 flood all companies irrespective of their size were interviewed in one campaign between May and July 2014. Due to this sampling procedure, the selection of companies was not representative, since it seemed more important to cover a broad range of companies in terms of size and sector. The person in the household or in the company with the best knowledge of the flood damage was always interviewed. To ensure a consistent comparison, only data from private households in Saxony (2002: $n = 977$; 2013: $n = 523$), Saxony-Anhalt (2002: $n = 271$; 2013: $n = 593$) and Bavaria (2002: $n = 449$; 2013: $n = 239$) and data from companies in Saxony (2002: $n = 415$; 2013: $n = 197$) were analysed in this study (Table 1).

Table 1. Survey using computer-aided telephone interviews with private households and companies affected by flooding in 2002 and 2013.

Flood event		August 2002 flood		June 2013 flood	
Target group		households	companies	households	companies
Survey method		Computer-aided telephone interviews using the VOXCO software package			
Survey period		April to June 2003	October 2003 and May 2004	February to March 2014	May to July 2014
Survey area, i.e. catchments and federal states		Elbe and Danube (Bavaria, Saxony, Saxony-Anhalt)	Elbe (Saxony)	Elbe, Danube, Rhine, Weser (Bavaria, Saxony, Saxony-Anhalt, Thuringia, Lower Saxony, Baden-Württemberg, Schleswig-Holstein, Brandenburg, Mecklenburg-West Pomerania)	Elbe, Danube, Rhine, Weser (Bavaria, Saxony, Saxony-Anhalt, Thuringia, Lower Saxony, Baden-Württemberg, Schleswig-Holstein, Brandenburg, Rhineland-Palatinate)
Number of completed interviews	entire survey area	1697	415	1652	557
	Bavaria	449	0	239	88
	Saxony	977	415	523	197
	Saxony-Anhalt	271	0	593	133
Length of interviews		About 180 questions – average duration 30 min	About 90 questions – average duration 15–20 min	About 180 questions – average duration 30 min	About 90 questions – average duration 34 min
Surveying institute		SOKO institute for social research and communication (http://www.soko-institut.de)		Explorare institute for marketing research (http://www.explorare.de)	SOKO institute (http://www.soko-institut.de)
Project partners		German Research Centre for Geosciences (GFZ), Deutsche Rückversicherung		University of Potsdam, German Research Centre for Geosciences (GFZ), Deutsche Rückversicherung	
References		Thieken et al. (2007)	Kreibich et al. (2007b)	Thieken et al. (2016a)	Thieken et al. (2016a)

All questionnaires addressed a broad range of topics: flood impact (e.g. water depth, contamination), flood warning, emergency measures, evacuation, cleaning up, characteristics of and damage to household contents and buildings, characteristics of and damage to company assets (buildings, equipment, goods, products or stock, etc.), recovery, precautionary measures, flood experience and awareness as well as socio-economic variables/characteristics of the company (sector, number of employees, etc.). Each topic was addressed with a number of questions. Most questions were closed, i.e. a list of possible answers was given (with either a single answer or multiple answers possible). For instance, for the question "How did you become aware of the imminent flood hazard for your company?" a list of possible answers was provided with multiple answers possible: public authority warnings; warnings by neighbours, friends, relatives, staff or other; general transregional media coverage; own observations. Thus, flood warning is treated in a broad sense, including official and unofficial warnings and even own observations.

In some questions people were asked to assess qualitative or descriptive variables on a scale from 1 to 6, where 1 described the best case and 6 described the worst case. The meanings of the end points of the scales were given to the interviewee. For instance, in response to the question "Did you know how to protect yourself and your household from the flood, before the flood became imminent for you?" people should state a number between 1 for "it was completely clear to me" and 6 for "it was completely unclear to me". The intermediate ranks could be used to graduate the evaluation. For a few questions, open-ended answers were requested.

To avoid errors as much as possible, only meaningful answers were accepted by the system. Wherever possible, answers were cross-checked; e.g. if the reported outside storage area was larger than the reported area of a premise, the interviewer was informed about this contradiction and prompted to clarify the situation. Per analysis, cases with missing values were excluded. Further details on the surveys and the data processing are published by Thieken et al. (2007, 2016a, 2017), Kreibich et al. (2007b) and Sieg et al. (2017). Answers provided to questions mainly related to flood warning and emergency measures are analysed for this study. Indicators of the warning source, warning content and effectively performed emergency measures were calculated as described in Thieken et al. (2005a, 2007).

5 Results and discussion

5.1 Warning reception by private households and companies

To respond to an upcoming flood, people need to be alerted through warnings or their own observations. To gain knowledge of the warning situation in Germany in 2002 and 2013, private households and companies were asked "How did you become aware of the imminent flood danger?" The responses show that in 2002 a total of 27 % of households and even 45 % of companies stated that they had not been warned at all and had not been aware of the flood danger before the flood reached them. In 2013, this fraction dropped to 5 % of private households and 3 % of companies (Table 2). However, regional differences, which could only be investigated for private households, were large: the overall picture is dominated by the results from Bavaria and Saxony where 29 and 32 % of households respectively, had not been aware of the imminent flood danger in 2002. In 2013, this fraction was significantly smaller with 4 and 3 % respectively. In contrast, in Saxony-Anhalt, located on the middle reaches of the Elbe river, only 6–7 % of households had not been warned or not been aware of the flood danger, with no significant difference between the two floods (Fig. 2). Warnings by public authorities were most important for becoming aware of the flood danger (Fig. 2). In 2002, 32 % of respondents in Bavaria, 36 % in Saxony and 81 % in Saxony-Anhalt indicated that they had received a warning by public authorities. In 2013, this fraction was significantly higher in Bavaria (66 %) and Saxony (55 %) but significantly lower in Saxony-Anhalt (61 %) (Fig. 2). It is interesting that the fraction of private households who became aware of the flood via their own observations increased significantly from 2002 to 2013 in all three investigated federal states (Fig. 2). This might be due to an increase in awareness and preparedness after 2002 (Kreibich and Thieken, 2009; Kreibich et al., 2011; Kienzler et al., 2015). With rather minor differences between the two flood events, warnings by neighbours, friends and relatives as well as the general transregional media coverage also played a role in warning private households (Fig. 2).

Also, for companies, flood warnings by public authorities played a considerable role during the floods of 2002 and 2013 (Fig. 3). However, in 2002, only 7 % of the surveyed companies received warnings from public authorities that had been directed specifically at the company and 16 % received general public authority warnings. In 2013, these fractions were considerably higher at 37 and 49 % respectively. However, during both floods (even strongly increasing from 2002 to 2013) most companies also became aware of the flood through their own observations. Additionally, it is important to warn companies through warnings by staff, relatives and others as well as through the general transregional media coverage (Fig. 3).

The private households that had received a warning by public authorities were additionally asked what information the warning contained (Fig. 4). It is interesting that only about a third of the warnings contained information about emergency measures, with no significant difference between the flood events. Thus, there is quite some potential for improving emergency communication to better support and trigger private damage reduction efforts. Most often the warnings contained information about peak water levels

Table 2. Information of all interviewed private households from Bavaria, Saxony and Saxony-Anhalt together (federal state specific information is provided in Figs. 2, 5 and 7) as well as from interviewed companies in Saxony.

Sector	Private households in Bavaria, Saxony and Saxony-Anhalt		Companies in Saxony	
	2002 ($n=1697$)	2013 ($n=1355$)	2002 ($n=415$)	2013 ($n=197$)
Fraction of interviewed households/companies				
– that had not received any flood warning and were not aware of the imminent hazard before the flood reached them	27 %	5 %	45 %	3 %
– for whom it was completely clear what to do when the warning reached them	14 %	44 %	na*	na
– for whom it was completely unclear what to do when the warning reached them	29 %	14 %	na	na
– that had never experienced a flood before the respective event	78 %	39 %	75 %	6 %
– that had not implemented any emergency measure	17 %	6 %	33 %	1 %
– that could have implemented (more) emergency measures if they had been warned earlier	51 %	24 %	74 %	25 %
Average (median) time spent on emergency measures (h)	13 (5)	31 (20)	13 (5)	22 (16)
Average (median) number of people involved in emergency measures	4 (3)	6 (4)	16 (6)	16 (10)

* na = question was not asked.

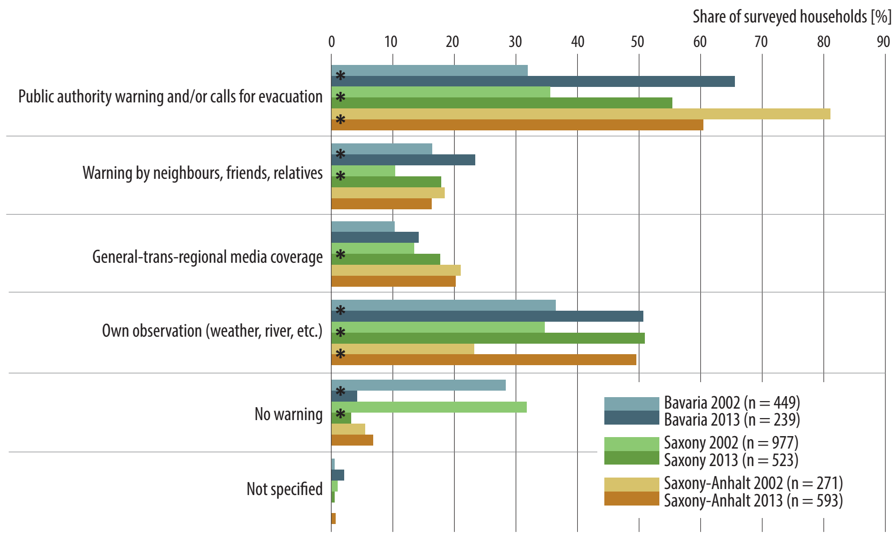

Figure 2. Answers of the interviewed private households in Bavaria, Saxony and Saxony-Anhalt in response to the question of how they became aware of the imminent flood danger (* indicates significant differences ($p < 0.05$) between 2002 and 2013).

(with a significantly higher frequency in 2013 in comparison with 2002 in Saxony and Saxony-Anhalt) and about areas at risk (with a significantly lower frequency in 2013 in comparison with 2002 in Bavaria and Saxony-Anhalt). Many warnings also contained information about evacuations, with a significantly higher frequency in 2013 in comparison with 2002 in all three federal states investigated (Fig. 4).

Since the response to warnings is believed to be strongly dependent on the warning lead time, private households and companies were also asked how many hours before the flood reached their house had they become aware of the flood danger. For both flood events there are large differences between regions; i.e. warning times were between 1 h and 14 days (data not shown). The average warning time in August 2002 was shortest in Bavaria at 17 h, and longest at the middle reaches of the Elbe River in Saxony-Anhalt at an average of 90 h (Table 3). In 2002 in Saxony, private households indicated an average lead time of 23 h and companies indicated

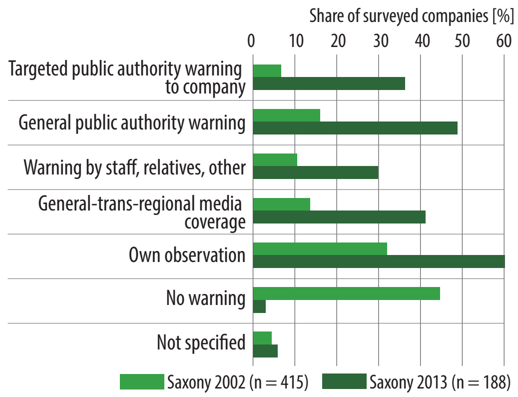

Figure 3. Answers of the interviewed companies in Saxony in response to the question of how they became aware of the imminent flood danger.

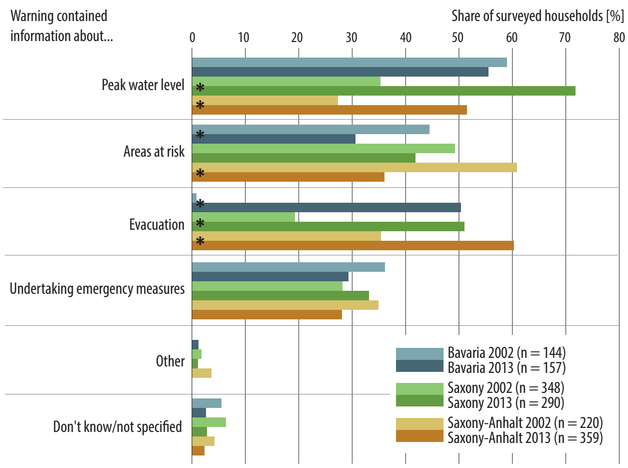

Figure 4. Information content of official flood warnings received by private households in Bavaria, Saxony and Saxony-Anhalt (* indicates significant differences ($p < 0.05$) between 2002 and 2013).

an average lead time of 20 h. In June 2013, lead times were significantly longer in Bavaria (average of 22 h) and Saxony (averages of 42 and 40 h for households and companies respectively). This increase in lead times might be explained by the improvement in the early-warning systems (see Sect. 3) as well as by less severe flash floods in 2013 in comparison with 2002 in Saxony and Bavaria (see Sect. 2). In Saxony-Anhalt lead times were significantly shorter in 2013 at an average of 42 h in comparison with 2002 (Table 3), reflecting the more severe situation at the Saale River and the middle reaches of the Elbe in 2013 in comparison with 2002 (Merz et al., 2014; BfG, 2014).

The significant improvement in the warning situation, with significantly more affected parties reached and longer lead times, in Bavaria and Saxony probably has three causes: firstly, the flood warning systems in Germany have been

Table 3. Mean (median) lead times indicated by private households and companies.

	2002 (h)	2013 (h)
Private households in Bavaria*	17 (8)	22 (16)
Private households in Saxony-Anhalt*	90 (96)	42 (24)
Private households in Saxony*	23 (10)	42 (24)
Companies in Saxony*	20 (8)	40 (36)

* Significant difference between years.

significantly improved after 2002 (Thieken et al., 2016b; DKKV, 2015), secondly, people and companies had more flood experience and were more aware of the flood risk (Kreibich and Thieken, 2009; Kienzler et al., 2015), so that they became aware of the imminent flood danger via their own observations more often and earlier and thirdly, the flood characteristics differed. In August 2002, severe flash floods occurred in the Ore Mountains, whereas the flood event in June 2013 developed slowly over several days (Conradt et al., 2013; Schröter et al., 2015). In contrast, in Saxony-Anhalt problems with warning system breakdowns occurred and the flood situation was aggravated in 2013 in comparison with 2002 (DKKV, 2015). As a result, slightly fewer people were warned and lead times were shorter in 2013 in comparison with 2002 in Saxony-Anhalt.

5.2 Emergency response by private households and companies

Early warning can only be effective if the people at risk trust the warning and know what to do when they receive a warning. Preparedness and recent flood experience seem to support the implementation of effective emergency measures (Kreibich et al., 2007b; Thieken et al., 2007). The flood experience differed strongly between the two flood events: in 2002, 78 % of interviewed private households and 75 % of companies stated that they had never experienced a flood before. In 2013, these fractions were only 39 and 6 % respectively (Table 2). Additionally, check lists are helpful for the implementation of emergency measures for private households, indicating what should be done and which things should be available in case of an emergency, and emergency plans and regularly undertaken emergency exercises are useful for companies (Kreibich et al., 2007a, b). The share of companies which had an emergency plan in place before the flood increased from 10 % in 2002 to 34 % in 2013 (Table 4). The share of those who had undertaken emergency exercises before the flood had increased from 4 to 14 % (Table 4). However, in this respect there is still room for improvement.

Households who had received a warning through public authorities were asked whether they knew how they could protect their household from the flood. In 2002 only 14 % of the interviewed households stated that it was completely

Table 4. Information by the company respondents from Saxony on their preparedness for and the effectiveness of emergency measures implemented.

Fraction of interviewed companies that	2002 ($n = 415$)	2013 ($n = 197$)
– already had an emergency plan before the flood	10 %	34 %
– already conducted flood emergency exercises before the flood	4 %	14 %
– were able to protect their equipment in its entirety or the most important part thereof	19 %	65 %
– were able to protect their goods, products and stock in their entirety or the most important part thereof	17 %	62 %
– were able to protect their vehicles in their entirety or the most important part thereof*	–	84 %

* Question asked only for 2013 flood.

clear to them what to do when the waning reached them; in 2013 this fraction was 44 % (Table 2). In contrast, in 2002, 29 % of the interviewed households stated that it was completely unclear to them what to do when the waning reached them; in 2013 this fraction dropped to 14 % (Table 2). Increased flood experience and improved risk communication, e.g. via information campaigns, presumably contributed to this development (Kienzler et al., 2015; Thieken et al., 2016b). However, there are some regional differences: there is no significant difference between the knowledge about emergency measures of private households in 2002 and 2013 in Bavaria (Fig. 5). This is in accordance with previous findings that revealed that households in Bavaria already knew what to do when warnings reached them in 2002, primarily due to their recent experience with the flood in 1999, in contrast to households in the Elbe catchment (Thieken et al., 2007).

Households and companies who had not undertaken any emergency measures were asked for their reasons (Fig. 6). The most often stated reason (irrespective of event and region) was that it had been too late to do anything, which stresses the importance of flood warnings and sufficiently long lead times. In 2002 it was additionally problematic that nobody was at home and that company properties could not be reached due to disrupted roads, which hardly played a role in 2013. It was already discussed in earlier studies that this lack of availability in 2002 was influenced by the fact that the flood happened during the summer holiday season in August (Thieken et al., 2007) and that severe damage to infrastructure had occurred (Kreibich et al., 2007b). More than 750 km of rural, county and state roads as well as 585 bridges were damaged in Saxony in 2002 (IKSE, 2004). Additionally, the flood hazard was underestimated. Many stated that they did not think the flood would become so severe, which was particularly the case in 2013 in comparison with 2002.

In 2013 considerably more private households and companies implemented emergency measures and put more effort into emergency measures in comparison with 2002 (Table 2).

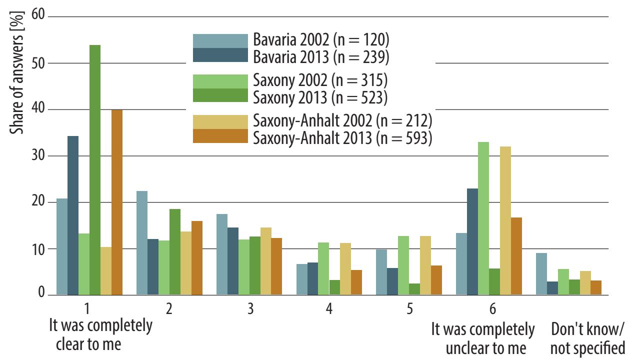

Figure 5. Answers of the households that had received a public authority warning, in response to the question whether they knew how to protect themselves and their household from the flood. Knowledge was significantly different ($p < 0.05$) between 2002 and 2013 in Saxony and Saxony-Anhalt (not in Bavaria).

In 2002, 17 % of private households and 33 % of companies had not implemented any measures, in comparison with 2013, when only 6 % of households and 1 % of companies had not implemented any emergency measures (Table 2). In 2002 private households and companies had on average 4 and 16 people involved in emergency measures respectively and spent on average 13 h on emergency measures. In 2013, on average 6 and 16 people were involved and spent on average 31 and 22 h on emergency measures by households and companies respectively (Table 2). However, regional differences exist, which were only investigated for private households: the overall picture is dominated by the results from Bavaria and Saxony where 21 and 17 % of households respectively had not implemented any emergency measures in 2002 (Fig. 7). In 2013 these fractions were only 8 and 3 % respectively. In contrast, in Saxony-Anhalt, i.e. in the middle reaches of the Elbe catchment, only 8 % of households had not implemented any emergency measures in 2002 and

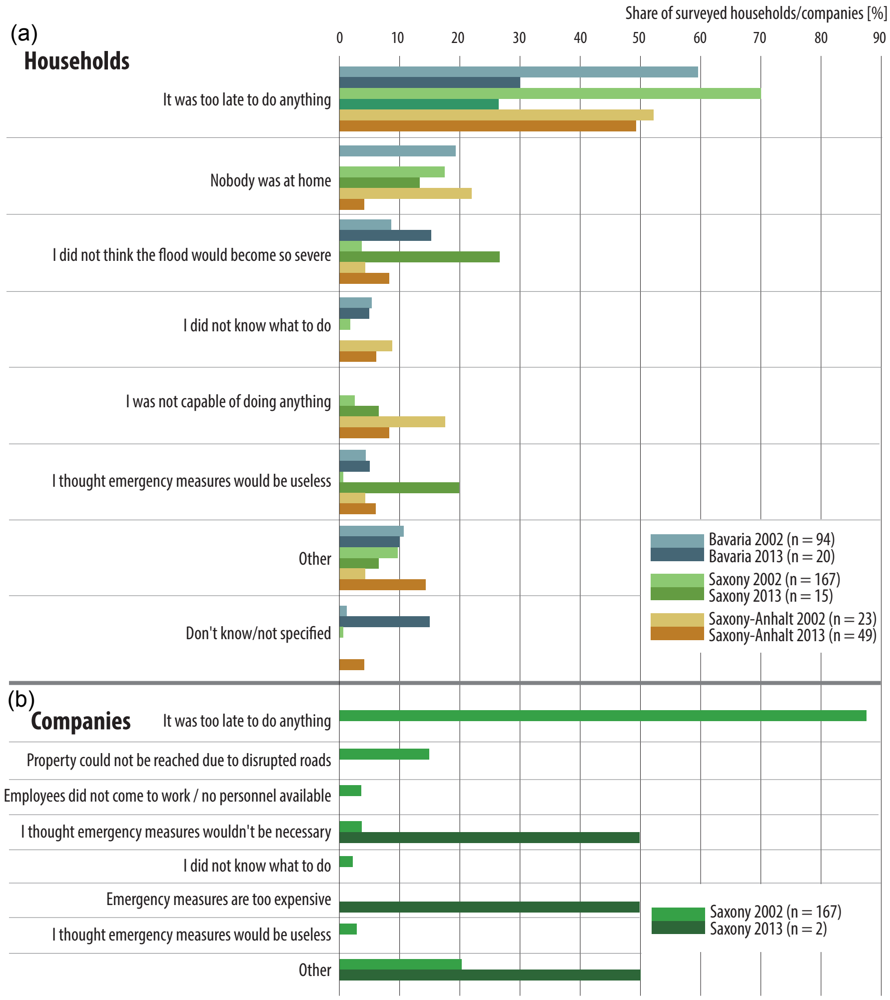

Figure 6. Reasons stated by households **(a)** and companies **(b)** in response to the question of why they had not performed any emergency measures (multiple answers possible).

2013 (with no significant difference between the two floods; Fig. 7).

Private households most commonly implemented the following emergency measures, irrespective of the flood event: "safeguard documents and valuables", "drive vehicles to flood-safe place" and "put movable contents upstairs/to safer place" (Fig. 7). Less common are the measures "protect building against inflowing water", "switch off gas/electricity, or was centrally switched off" and "secure oil tanks etc.". Besides emergency measures like protecting equipment, goods, etc., as well as protecting vehicles (Table 4), companies also undertook other measures like setting up water barriers, mainly using sandbags and the deployment of pumps as well as securing any other movable items (data not shown).

In the case of the 2002 flood, 51 % of households and 74 % of companies stated that they would have been able to implement (more) emergency measures if they had been warned earlier; in 2013 these fractions were only 24 and 25 % respectively (Table 2). This means that in 2002, most surveyed households and companies had too little time to implement emergency measures, while in 2013 most of them had sufficient time. This probably also influenced the fact that in 2013 the perceived effectiveness of the implemented emergency measures of private households and companies was generally rated higher in comparison with 2002. Figure 8 presents the self-perceived effectiveness reported by the surveyed households on a scale after the flood event; i.e. it shows an evaluation by flood-affected people concerning how much damage was prevented through a specific measure. The effectiveness of most emergency measures implemented in 2013 in Saxony and Saxony-Anhalt received significantly higher ratings than the ones implemented in 2002 (Fig. 8). In 2013, far more companies were also able to protect the most important parts of their equipment as well as of goods, products, etc. (Table 4). In contrast, in Bavaria the perceived effectiveness of the emergency measures was

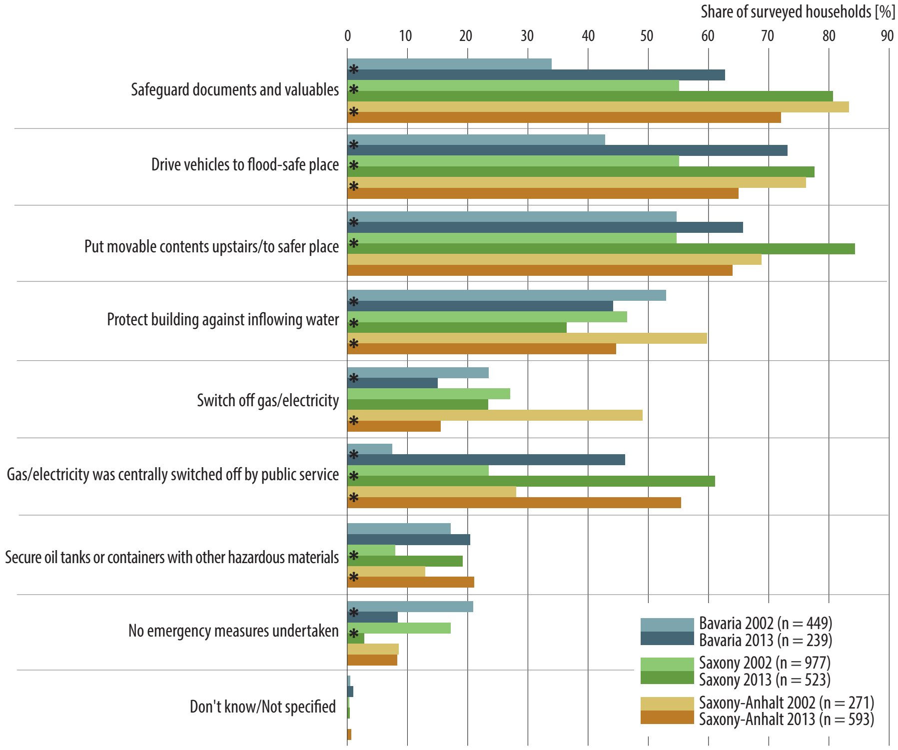

Figure 7. Overview of the emergency measures undertaken by the interviewed households in Bavaria, Saxony and Saxony-Anhalt (semi-open question, multiple answers possible, * indicates significant differences ($p < 0.05$) between 2002 and 2013).

similar for both flood events (Fig. 8). Generally, "safeguard documents and valuables" and "drive vehicles to flood-safe place" were perceived as the most effective measures. Other measures were perceived to be slightly less effective; with respect to their effectiveness ratings these are in decreasing order: "switch off gas/electricity", "secure oil tanks etc.", "put movable contents upstairs/to safer place" and "protect building against inflowing water". The measures "safeguard documents and valuables" and "drive vehicles to flood-safe place" were implemented very often by households and their effectiveness was rated very high (Figs. 7 and 8). Unfortunately, a previous study revealed no damage-reducing effect of these emergency measures even when implemented very effectively (Thieken et al., 2005a). The highest damage-reducing effect of very effectively implemented emergency measures was shown for "protect building against inflowing water" and "install water pumps" (Thieken et al., 2005a).

Generally it is assumed that more emergency measures can be implemented in an effective way when lead times are long, flood intensity is low and when the affected parties are well experienced and prepared (Penning-Rowsell and Green, 2000; Molinari and Handmer, 2011; Mross et al., 2016). To investigate such possible links, the Spearman rank correlations between the indicator of effectively performed emergency measures and other parameters are calculated (Table 5). Generally, correlations are relatively weak, all below 0.45. For companies in 2013 no significant correlations exist probably due to the small sample size and high heterogeneity of the data. Still, the warning parameters quite clearly show the highest correlations with effective emergency measures, with the most important parameter being the lead time, followed by the source of the warning and the information contents of the warning. Additionally, the efforts undertaken for emergency measures, i.e. time spent and number of people involved, are also relatively strongly correlated with effectively performed emergency measures. Surprisingly, flood intensity and preparedness parameters are less correlated with effectively performed emergency measures (Table 5).

6 Conclusions

The comparison of warnings received and emergency measures undertaken by private households and companies before and during the 2002 and 2013 flood events generally show a clear improvement. Thus, the various initiatives and high investments undertaken to improve flood risk management after 2002 in Germany were successful. The warning reached significantly more affected parties and reached them with longer lead times in 2013 in comparison with 2002. In addition, the share of official warnings by public authorities which reached the affected parties increased from 2002 to 2013. The marked decline of affected parties who had not re-

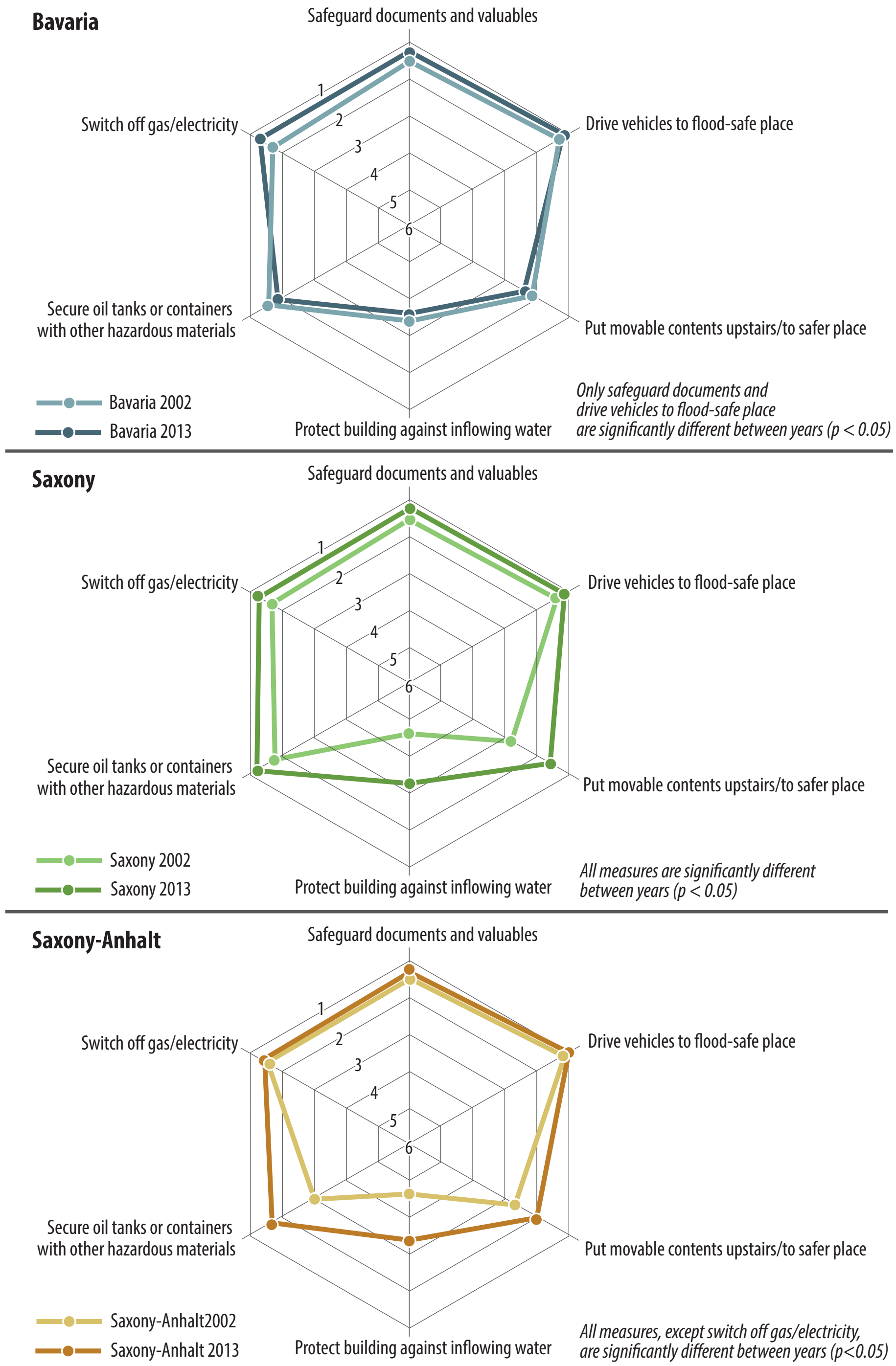

Figure 8. Self-perceived effectiveness of undertaken emergency measures by interviewed households in Bavaria, Saxony and Saxony-Anhalt (1 means very effective and 6 means not effective at all).

ceived any warning and the increases in lead times are probably due to the improvements in the warning systems, increased risk awareness and preparedness and the fact that in 2013 the evolution of the flood event was clearly less dynamic than in 2002. In 2013 most surveyed households and companies had sufficient time to implement emergency measures, illustrating that increasing the lead times is no longer a pressing issue, except for flash floods. Only about a third of the warnings contained information about emergency measures, with no significant difference between the flood

Table 5. Rank correlation (Spearman's rho) between the indicator of effectively performed emergency measures and other parameters (only coefficients significant at the 0.05 level and > 0.1 are shown).

	Parameters	Private households		Companies	
		2002 ($n=1697$)	2013 ($n=1355$)	2002 ($n=415$)	2013 ($n=197$)
Flood intensity	Water depth (cm)	–	–	−0.18	–
	Perceived flow velocity (0 = still to 6 = very high velocity)	−0.13	–	na*	–
	Flood duration (h)	0.14	–	–	–
Warning	Warning source (indicator)	0.28	0.11	0.24	–
	Warning information (indicator)	0.26	0.12	na	na
	Lead time (h)	0.40	0.15	0.42	–
Effort for emergency measures	Time spent on emergency measures (h)	0.37	0.28	0.31	–
	Number of people involved in emergency measures	0.18	0.20	0.15	–
Preparedness	Emergency plan available (yes/no)	na	na	–	–
	Frequency of undertaking emergency exercises	na	na	0.12	–
	Perceived knowledge about self-protection (1 = "completely clear what to do" to 6 = "completely unclear what to do")	–	-0.21	na	na
	Number of floods experienced before event	–	0.14	0.11	–

* na means that the question was not asked.

events. Thus, emergency communication should be improved and the link between early warning and emergency response should be strengthened. The general boost in information and awareness campaigns after the flood in 2002 has probably supported an improved knowledge of households and companies about how they can protect themselves against flooding. Furthermore, increased flood experience played a significant role. This became apparent in the amount of emergency measures implemented as well as in the self-evaluation of their effectiveness by private households and companies. In the case of companies the increase in available emergency plans and regularly conducted emergency exercises points to an increased preparedness. However, particularly with respect to emergency plans and exercises there is still room for improvement. Probably, integrating companies and private households into transnational exercises, like the biennial transnational crisis management exercise LÜKEX in Germany, could significantly improve preparedness and support an effective realization of an emergency response by affected parties.

Some regional differences are apparent: in Saxony, significantly more affected parties were alerted, and lead times were significantly longer in 2013 in comparison with 2002. Additionally, significantly more households and companies had implemented emergency measures and evaluated these to be significantly more effective in 2013 in comparison with 2002. In Saxony-Anhalt, the warning situation was already relatively good in 2002, so that no significant improvements were apparent with respect to the fraction of households reached by warnings as well as to the lead time. The more severe flood situation in 2013 in comparison to 2002, however, challenged the system, which should be accounted for in future efforts to advance underlying models and the IT system, as well as to employ enough and well-trained personnel that are capable to cope even with long-lasting events. In Bavaria, in 2002 households had recent flood experience due to a severe flood event in May 1999 and were relatively well prepared. Thus, hardly no significant difference in the perceived effectiveness of undertaken emergency measures were apparent between 2002 and 2013 in Bavaria.

Floods may become more frequent and more extreme in several regions due to the effects of climate change, which implies that floods may increasingly affect areas with no or little prior flood experience. Thus, the challenge is to continuously maintain and advance integrated early-warning systems. This includes keeping preparedness high and supporting effective emergency response by affected parties even without prior flood experience and the push of extreme events (Kreibich et al., 2017). To further increase lead times and support an effective response, rainfall and flood forecasts, particularly in flash flood areas, should be further improved and complemented with uncertainty and impact assessments (Thieken et al., 2016b; Dottori et al., 2017). Effective and harmonized risk and emergency communication, e.g. via combining hazard and risk information with information on adequate risk-reducing behaviour, can help to motivate behavioural precaution, to keep preparedness of residents and company owners high and to support effective emergency response. Risk information campaigns should include the set-up of flood marks, compilation and dissemination of hazard and risk maps, creative educating ideas, as well as the communication of precautionary and coping strategies (Thieken et al., 2016b). Since information requirements and response capacities vary, certain subgroups (e.g. homeowners, tenants, companies of different size and economic sectors) should be identified and addressed by tailored information and media. However, suitable incentives would additionally be helpful for triggering preparations like the development of emergency plans or undertaking regular emergency exercises. Generally, the implementation of an integrated early warning and emergency response concept has advanced after recent flood events and now more efforts should be undertaken to continuously improve and maintain it.

Data availability. Parts of the data are available via the German flood damage database HOWAS21 (GFZ, 2017).

Competing interests. The authors declare that they have no conflict of interest.

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