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Volunteered Geographic Information for Disaster Management with Application to Rapid Flood Damage Estimation

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Abstract

All phases of disaster management require up-to-date and accurate information. Different *in-situ* and remote sensor systems help to monitor dynamic properties such as water levels or inundated areas. New Internet technologies have facilitated fast and easy data collection from the public, giving rise to the idea of using Volunteered Geographic Information (VGI) to aid disaster management. This paper discusses the opportunities and challenges of using VGI for disaster management with particular focus on information for the response and recovery phases. Different approach to assessing VGI data quality are presented and discussed. In a case study, the fitness for use of observations from the affected population for rapid flood damage estimation is demonstrated to be comparable to estimates based on hydraulic modelling. Further research needs with respect to the case study and to VGI for disaster management in general are identified.

1 Introduction

Natural hazards cannot be prevented, however, measures can be taken to mitigate their impacts and prevent them from becoming disasters. Disaster management is a continuous process that aims at avoiding or reducing the impact of natural hazards. All phases of disaster management require up-to-date and accurate information. Information from many different sources has to be integrated, including different *in-situ* sensors, such as water gauges or seismometers, and aerial and satellite images. So far, observations of eye witnesses other than emergency staff are rarely taken into account systematically.

Recent disasters have shown that information contributed by eye witnesses via the Internet can greatly improve situational awareness. For example, when a magnitude 7.9 earthquake hit the Chinese province of Sichuan in 2008, within one minute the first discussion thread appeared in a popular Chinese Internet discussion forum, followed quickly by others discussing observations of the earthquake and its impacts and even organising help actions (Yan et al., 2009). After the 2007 wildfires in southern California, local residents shared their observations using social networking or local news web sites, some of them using Google

Maps to allow users to localise the information they contributed. This information was judged to be more useful than national news or official government web sites by other affected residents (Sutton et al., 2008). The potential of spatial information collected by volunteers from the public and shared over the Internet, so called "volunteered geographic information" (VGI), is increasingly being recognised and discussed. VGI offers a great opportunity to enhance awareness because of the potentially large number of volunteers to act as "sensors" observing important disaster management parameters in their local environment. However, a number of issues and challenges arise that need to be addressed for this information to be useful.

The next section introduces the concept of disaster management (DM) and discusses the opportunities and challenges of using VGI to support DM. Section 3 specifically addresses the problem of assessing and ensuring the quality of VGI for DM. In section 4, a case study is presented that focusses on assessing the quality of VGI for rapid flood loss estimation by example of the 2002 flood event in Eilenburg (Mulde), Germany. The paper ends with a discussion of the concepts and some conclusions for further research.

2 VGI for natural disaster risk management

Disaster management is a process that includes activities before, during and after a hazard event that aim at preventing disasters, reducing their impacts and recovering from their losses. The disaster management process is often interpreted as a cycle consisting of four main phases: mitigation, preparedness, response and recovery. These phases and examples of associated activities are illustrated in Figure 1.

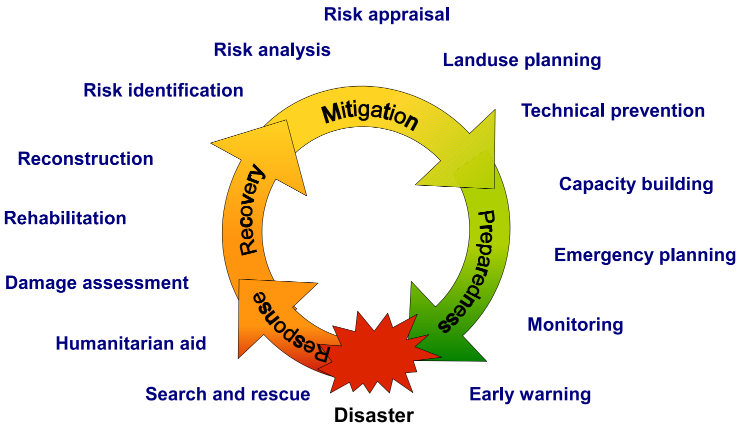

Figure 1: The phases of the disaster management cycle and examples of related activities (modified from Thieken et al., 2007)

- Disaster mitigation is a continuous process focussed on reducing or eliminating risk. It includes risk identification, analysis, and appraisal, as well as risk reduction by means of spatial planning, technical measures, and public awareness and education.

- Preparedness deals with planning how to respond to hazardous events. It comprises emergency planning and training as well as the installation and operation of monitoring, forecasting, and early warning systems.

- In case of a disaster, response measures aim at maintaining or reestablishing public safety by search and rescue operations, and measures to provide for the basic humanitarian needs of the affected population.

- Post-disaster recovery is the process of restoring the living conditions in the affected areas. It includes rapid damage assessment as well as rehabilitation and reconstruction.

In all of these phases, the parties involved require different kinds of static or dynamic spatial information, which need to be accurate and up-to date. To get as complete an overview of the situation as possible, information from many different sources has to be integrated. While most information is in general supplied by public agencies, specialised companies, research institutions or practitioners in emergency management, the public is increasingly recognized as a valuable source of information (Goodchild, 2007a; Pelling, 2007). The idea to use human observations to enhance environmental knowledge or improve spatial planning processes is not new. Extensive research in "citizen science" and public participation geographic information systems has proved the usefulness of involving the public in environmental monitoring (e.g. Fore et al., 2001; Engel and Voshell, 2002) and spatial planning (e.g. Weiner and Harris, 2003; Sultana et al., 2008). However, until recently, collecting information from the public by telephone, mail, or personal meetings was time-consuming and often costly, and the organizational effort for such surveys rendered it useless for any kind of time-critical tasks. Advances in ICT, particularly new Internet technologies and use patterns, often termed "Web 2.0", have made data collection from volunteers easier and faster, thus making it possible to collect information from volunteers systematically on a large scale (Gouveia et al., 2004).

In different phases of disaster management, different kinds of information volunteered by the public can be important. The mitigation and preparedness phases are long-term processes that mostly require information that can be considered static within the time frame of one iteration of the disaster management cycle. Examples for this kind of information include information on identification and quantification of hazards, vulnerability parameters such as land use and distribution of assets or information for emergency action planning such as location of hospitals. In particular in areas where few long-term records on disasters exist, the local population's knowledge about location and extent, frequency and intensity of past natural disasters can be of high value. A change of paradigm from a strong focus on technical protection to integrated risk management has been observed by Merz and Emmermann (2006). Integrated risk management includes the five steps risk identification, risk analysis, risk appraisal, risk reduction and coping with residual risk, all accompanied by a risk dialogue involving all stakeholders. This process should include open discussion of acceptable risk and mitigation options, in which the public is an important stakeholder. The main contribution the public can make in these phases via VGI is to communicate their views and perceptions about acceptable and unacceptable risk, coping strategies, possible mitigation measures and their prioritisation.

In contrast to the long-term processes of mitigation and preparedness, the response and, to some extent, the recovery phase require highly dynamic data, describing the extent and intensity of the hazardous event as well as resulting impacts and the current status of response activities. Examples of such data are observations of water levels and inundated areas, damages to infrastructure or the location of rescue teams. These parameters need to be monitored continuously and updated regularly.

Different *in-situ* sensors have been used for decades to monitor hazard-related parameters such as precipitation, water levels or ground movements. Advances in information and communication technology have helped to make data from such sensors available online in near real time. While there are many different kinds of sensors measuring physical, chemical and biological phenomena, these sensors are usually highly specialised, i.e. they measure only one or very few parameters. Also, these sensors are mostly stationary, and their locations are the result of careful planning and optimisation. Remote sensing systems are another important source of up-to-date data about the earth's surface that supply valuable information for disaster management. With an increasing number of satellites, higher spatial and temporal resolution, and different kinds of active and passive remote sensing systems available, remotely-sensed data are gaining importance in all phases of disaster management (Tralli et al., 2005; Voigt et al., 2007). They can supply many different parameters that are detectable from above for disaster management such as inundated areas or extend of forest fires.

Despite recent advances in both *in-situ* and remote sensing systems, there are still some phenomena that cannot be sufficiently measured such as hailstorms, which are very local events, yet have great destructive power, or damages caused by natural hazards. Also, measurements from sensor systems may not be available due to interruption of communication or destruction of sensors, such as water gauges that can be destroyed by very severe floods. Moreover, sensors may not be able to take measurements at critical moments as often happens in severe weather conditions when images from optical remote sensing systems are obstructed by clouds. For remote sensing, also a time delay occurs due to data acquisition and processing. Some of these gaps may be filled by VGI. Goodchild (2007b) has proposed to consider humans as sensors as they observe their environment and can synthesize and interpret local information. In contrast to physical sensors, humans have different senses and with these can observe different parameters. Also, they can move freely, they have local knowledge, are aware of their surroundings and can make sense of situations. Therefore, the information they provide is filtered and contextual. Moreover, people may provide information about phenomena which cannot or are usually not measured by any sensors such as occurrence of hailstorms or specific damages. Table 1 shows examples of the information human sensors can collect for disaster management.

Table 1: Examples of parameters humans can observe that may be useful for disaster management

Sense	Examples of use for disaster management
Sight	Observation of many parameters including water levels, occurrence of hail storms, damages
Hearing	Detection of creaking sound for earthquake intensity estimation
Smell	Detection of air pollution or fires
Taste	Detection of drinking water pollution

Few examples exist in which VGI is systematically taken into account in disaster management. A notable exception are the community Internet intensity maps that the US Geological Survey produces based on information collected from the public via a web interface called “Did you feel it? (Wald et al., 1999). Within this project, that started in the 1990s, the affected people report on hundreds of earthquakes per year; depending on the location and intensity of the earthquake, up to tens of thousands of reports are filled for a single event. Wald et al. (1999) evaluated the maps produced from VGI and could show that the results were robust and useful for seismic risk analysis.

3 Challenges of using VGI for disaster management

Despite the obvious advantages of involving the public in gathering information relevant for disaster management, there are a number of challenges. The main limitations of data collected from the affected population that impede their use are:

- Availability: It is unknown beforehand, how much and which and from where information will be supplied. Unlike a sensor network, information collection from the public cannot be planned in advance so as to yield an optimal configuration of observations for the phenomenon of interest. Therefore, for important information, volunteered information should only be supplementary to other data sources.

- Data quality: One of the major obstacles for using VGI is its unknown quality. The general population is not trained to make specific observations needed in disaster management and may intentionally or unintentionally contribute erroneous information. If affected by a disaster, humans can be very emotional which may impair their observations. Also, they may intentionally exaggerate a hazard's impact in order to gain personal advantages in compensation.

- Bias towards severe events: The more severe an event and its impacts, the more likely the affected persons may be to report it. Therefore, only events above a certain threshold are likely to be reported at all, and for the reported events, a bias towards more severely affected people and areas can be expected.

- Localisation: While *in-situ* sensors are in general stationary at known locations, and remotely sensed data are operationally georeferenced, human observations need to be localised in order to be useful. Until recently, the two main options were a) asking for address data and geocoding these, which only works well within settlements, or b) asking the volunteers to indicate the observation locations on maps or aerial images. The increasingly widespread availability of GPS-enabled consumer devices such as mobile phones, however, may help to make localisation of observations easier.

- Data collection: One way of obtaining the information, that is required for a specific task, is structured data collection by Internet-based surveys. This approach has the advantage of yielding exactly the information required in the desired format, however, it requires volunteers to know about and be willing to complete such surveys. Yet a much larger amount of information is distributed over various social networking services and other web sites. While this information may be easily accessible, filtering vital information out of the vast amount of data and integrating it with information from other sources poses a challenge in time-critical situations.

Of these challenges, data quality is discussed in more detail in the next section and explored in a case study.

3.1 Quality of VGI - Accuracy and Credibility

To tap the potential of VGI for disaster management, it is essential to systematically assess the quality of data that anonymous and untrained people supply via the Internet. Methods need to be developed to support quality control in on-line information systems using these data. VGI can be assessed in its quality either as accuracy or as credibility. These two concepts are discussed in the following.

Mapping agencies and other traditional geodata providers have extensive mechanisms to ensure delivery of high-quality data based on standardised and well-documented quality models and quality management procedures. These include quality control procedures for data capture, data storage, data processing, and data delivery as well as independent checks for quality assurance (Harding, 2006). Information on data content and data quality as described by several data quality elements are usually included as metadata with the spatial data. For example, ISO45 (2002) defines 5 quantitative data quality elements (completeness, logical consistency, positional accuracy, temporal accuracy and thematic accuracy) and 3 non-quantitative elements (purpose, usage and lineage). The use of such formal standards, their official mandate, professionally trained personnel, and long traditions in mapping add authority to the data provided by mapping agencies. The data quality assessment of the data providers focusses on the level of similarity between the data produced and the real-world phenomena they describe (or rather the data that should have been produced according to the data model, if no errors were made) (Devillers and Jeansoulin, 2006). This approach is termed "internal data quality" by Devillers and Jeansoulin (2006) and "quality-as-accuracy" by Flanagin and Metzger (2008). Devillers and Jeansoulin (2006) point out "external data quality" or "fitness for use" as a complementary concept, which assesses the suitability of a data set for a specific task in a specific area. External data quality assessment relies on the measures of internal data quality and explicitly stated objectives and requirements of the intended use. The requirements and the data specifications are matched to evaluate one or more data sets for their suitability for the task at hand.

A different concept of data quality is often applied in the Web 2.0 context where large amounts of user-generated content pose new challenges: credibility. While accuracy is an objective, albeit difficult to assess, property of information, that describes how well data represent phenomena, credibility is a subjective perception on the part of the data user (Flanagin and Metzger, 2008). Credibility is based on trust and reputation as proxies for data quality; it relies on the users to rate the credibility of other users and the information they contributed. This concept can be interpreted as an implicit evaluation of external data quality: it also aims at the usefulness of data as perceived by their users. This evaluation, however, is done intuitively rather than by explicitly matching stated requirements and data specifications. This "quality-as-credibility" (Flanagin and Metzger, 2008) is particularly useful when individual perceptions or vague concepts are aimed at rather than objective properties. It can only be applied if there is an information community of users who collaboratively provide information and rate each other's contributions to allow for trust and reputation modelling (Bishr and Mantelas, 2008). Most Internet communities providing VGI such as Wikimapia (www.wikimapia.org) rely on such a network of registered users who contribute regularly and whose contributions can be rated and verified by other users. Trust has many facets and is always context-dependent (Bishr and Mantelas, 2008; Golbeck, 2009). Bishr and Mantelas (2008) have proposed an extension of currently used trust models that introduces geographic proximity as one additional dimension of trust based on the assumption that proximity causes similarity, and thus trust. While this kind of trust and reputation modelling is most often applied in web-based information communities, Flanagin and Metzger (2008) argue that it is rather the content of the data than the way they were collected that should determine which approach to data quality - quality-as-accuracy or quality-as-credibility - should be adopted. If the data is rather factual in nature, traditional internal and external quality measures can be applied, whereas information aiming at opinions or vague concepts should be assessed using trust and reputation modelling.

As we have pointed out, in different phases of the disaster management cycle, different kinds of information volunteered by the public can be useful. In some tasks of the mitigation and preparedness phases such as land-use planning or prioritising of prevention measures, the public can volunteer opinions and contribute to discussions on priorities or advantages and disadvantages of measures to be taken. In these processes, which ideally consist of continued exchange of opinions and perceptions rather than facts, an information community exists. Therefore, for these processes, the quality-as-credibility approach is suitable. In the response phase, however, the affected population supplies information ad hoc, without training, and not regularly. To encourage as many people as possible to contribute information in this phase, a system should be as open as possible which includes not requiring user registration. Since mostly factual information about hazardous events and their impacts is required, the quality-as-accuracy approach is to be preferred.

4 Case study: Assessing the quality of VGI for rapid flood damage modelling

In this case study, we explore the potential advantages and challenges in using VGI for disaster management. After a hazardous event, it is important to get an estimate of the damage caused as soon as possible. For rapid flood damage estimation, the most important event parameter is the spatial distribution of inundation depth. Since these data are not always easy to get quickly, we envisage using observations by the affected population as an (additional) data source, collected in a web-based system similar to the USGS' "Did you feel it?" initiative. The aim of this preliminary study is to assess the feasibility of such an approach by analysing data on inundation depth collected from the affected population. These data were obtained in telephone interviews conducted 6 months after the 2002 flood in the Elbe river basin.

For this study, the municipality of Eilenburg, located on the Mulde River in Saxony, was selected (see figure 2). Eilenburg was heavily affected by the 2002 flood in the Elbe River basin and its subcatchments, and a number of studies on inundation depth and monetary damage exist that are used to compare the results to (Apel et al., 2009; Schwarz et al., 2005).

Although this study focuses on VGI, the traditional approach to internal and external data quality is used, since the information required consists of objective properties. Also, as the users are supposed to be people affected by floods, there will not be a community of regular users whose reputation can be assessed but rather different anonymous contributors for each flood event. The main focus will be on attribute accuracy for inundation depth observations from the public as well as fitness for use of these data for empirical flood damage modeling.

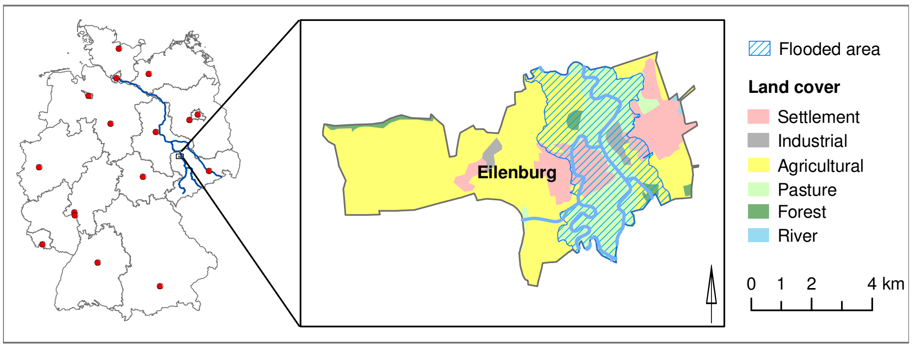

Figure 2: Location and overview of the study area with inundated areas during the 2002 flood

4.1 Rapid flood damage estimation using empirical models

For public administrations, but also for insurance companies, it is important to get an estimate of the expected monetary damage as soon as possible after a disaster. Direct monetary damages can be estimated using empirical damage or loss functions. For floods, these models calculate the expected damage as a function of inundation depth, building characteristics, and possibly further parameters such as water contamination. While building characteristics can be obtained from statistical and census data as they change only slowly, the spatial distribution of inundated areas and inundation depth is specific to a flood event and thus needs to be assessed specifically for each event. There are several methods to estimate inundation depths for flooded areas that are currently used for rapid damage assessment:

- Water gauges and digital elevation models (DEMs): Water gauges provide data on water levels at specific points in the river channel, but not inundation depths in flooded areas. Using a DEM, water levels from the river channel can be interpolated to the floodplain area. However, not all rivers are gauged, and very severe flood may damage or destroy gauges. Also, if dykes are not adequately represented in the DEM, results can be very inaccurate.

- Flood mask from remote sensing and DEMs: The extent of inundated areas can be retrieved from active or passive remote sensing systems. These maps do not contain information about inundation depth, however, inundation depth can be calculated using DEMs. The temporal resolution of remote sensing systems can be a problem for flash floods and rapid-onset floods, so that the time of peak discharge and inundation may be missed. For passive systems, also clouds can pose problems.

- Hydraulic modelling: Hydraulic models can be used to transform the discharge measured at gauges into inundation extent and depths. Gauge measurements are usually required for calibration. Hydraulic models are the most sophisticated approach, however, setting up and calibrating a hydraulic model to reconstruct a flood event is a time-consuming process which can often not be accomplished within a few days.

Because of the problems associated with all these data sources, using inundation depth measured or estimated by the affected population may be a useful addition for rapid flood damage assessment.

4.2 Data and Methods

Input and validation Data

The following data were available for the analysis:

- Information from the affected population was available from telephone interviews performed six months after the flood in the Elbe and Danube River catchments in 2002 (Thieken et al., 2005). In this survey, almost 1700 randomly sampled people affected by the flood were asked to provide information on flood parameters, preventive measures they undertook and damage that were caused by the flood at their home. Of these, data on inundation depth are used in this study. For more a detailed description of this survey, see Kreibich et al. (2005); Thieken et al. (2005)
- A digital elevation model with a resolution of 25 meters was provided by the Saxonian land surveying office.
- For the accuracy assessment, measured inundation depth from water marks at 409 buildings in the community of Eilenburg on the Mulde River were available from Schwarz et al. (2005).
- For several communities within the Mulde River catchment, inundation of the 2002 flood was modelled by Apel et al. (2009) using hydraulic models of different complexity.
- An estimate of the total damage to residential buildings caused by the 2002 flood was available from the Saxonian Relief Bank (SAB) for the municipality of Eilenburg.

Methodology for accuracy assessment

As the location of the data from the telephone interviews was specified by the street address, these data first had to be geocoded in order to be used in spatial analyses. The first analysis was to compare the estimated inundation depth data from the telephone interviews with the measured inundation depth from Schwarz et al. (2005). As the locations of the different point data did not coincide, the measured data were interpolated. However, as the water surface is considered to be more strongly spatially autocorrelated than the actual inundation depth, the height of the water surface was calculated by adding interpolated terrain heights to the measures inundation depth. Then, the height of the water surface was interpolated to the locations of the interview data using Universal Kriging. To yield inundation depth, the terrain height was subtracted. These data were compared to the estimated inundation depth from the interview data.

In the next step, inundation depth from both the measured data and the interview data was interpolated onto a regular grid using Universal Kriging and then used as input for flood damage modelling. Monetary damage to residential buildings was modelled using the empirical Flood Loss Estimation Model for the private sector (FLEMOps) on the meso scale (Thieken et al., 2008). This model calculates the damage ratio for residential buildings as a function of inundation depth classified into five classes and building characteristics, i.e. three buildings types and two building qualities. To be applicable on the meso scale, mean building composition and the mean building quality per municipality were derived by Thieken et al. (2006). The resulting damage ratios are multiplied by total asset values disaggregated to land use units (Kleist et al., 2006; Thieken et al., 2006). The resulting damage estimates were compared to results obtained with hydraulic modelling as well as to the damage estimates of the Saxonian Relief Bank.

4.3 Results of the case study

For water level, the comparison with measured data yielded a Root Mean Squared Error (RMSE) of 0.76m and a bias of 0.37m. A scatterplot of the measured versus estimated inundation depth is given in Figure 3. The different skewness of the distributions may be due to the collection method of the telephone interviews: since the aim of the interviews were damage as well as event data, only households that had suffered losses were interviewed, therefore creating a bias towards higher inundation depths. Although the deviations may seem high, they correspond quite closely to the accuracy achieved by hydraulic modelling for the same flood event in the same area. Depending on the model used, hydraulic modelling yielded a RMSE of 0.82-0.88m and a bias of -0.03-0.3m, and still these data proved to be useful for damage estimation (Apel et al., 2009). Since the flood loss model FLEMOps uses classified water levels as input, the data were also compared after classification into the classes used by the model. As can be seen in Figure 3, 60% of the values fall within the same class, and only 3% deviate by more than one class.

Figure 4 shows the inundation depth in the municipality of Eilenburg as obtained from hydraulic modelling, from interpolation of measured inundation depth data and from interpolation of inundation depth estimated by the affected population. The absolute values of all methods fall within a very similar range. While the patterns of the surfaces interpolated from measured and VGI data are quite similar, the modelled surface shows a somewhat different pattern.

The results of the damage estimation with FLEMOps are summarised in Table 2. The results of all three methods are comparable and all consistently

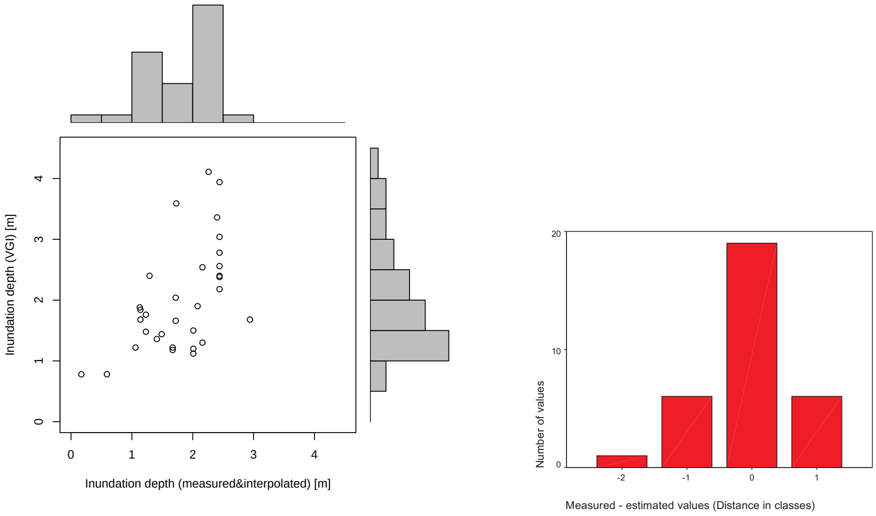

Figure 3: Deviation of estimated inundation depth from measured and interpolated inundation depth. Left: Scatterplot with histogram. Right: After classification for FLEMOps (Classes: 0cm, 0-20cm, 20-60cm, 60-100cm, 100-150cm, >150cm)

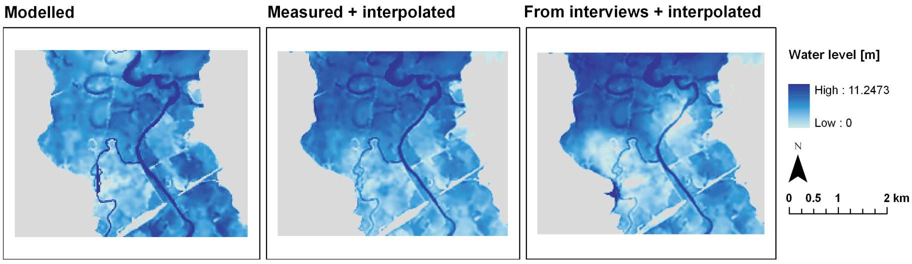

Figure 4: Inundation depth from a) hydraulic model, b) Measured at buildings and interpolated and c) estimated by the affected people and interpolated

underestimate the damages by about 35 to 40% in comparison with the estimate of the Saxonian Relief Bank. Considering the overall uncertainties that are associated with empirical flood loss modelling (Merz et al., 2004), these results can be considered as useful for rapid damage estimation.

Table 2: Estimated total damage to residential buildings in the municipality of Eilenburg for the 2002 flood in M €

Reference value (SAB)	Hydraulic modelling	Interpolation of measured water levels	Interpolation of water levels from interviews
77.12	50.28	45.3	50.81

5 Discussion and conclusions

The usefulness of information volunteered by the affected population has been demonstrated for the specific example of rapid flood damage estimation. These results need to be further validated by looking at more and different study areas and types of floods. So far, only the general usefulness of this information for rapid flood loss estimation has been shown. For such information to be used operationally, it will be necessary to establish automated methods for quality control including the detection of outliers and an assessment of estimation uncertainty. Also, integrating the observed inundation depth with other types of sensor data such as water level measurements in the river channel and inundation masks from remote sensing systems may further enhance the quality of the results.

We have shown that VGI can be a great opportunity to support and improve disaster management. However, much further work is required to allow to fully exploit this potential. Most importantly, methods for quality control of such information need to be developed. Due to the diversity of information that the public could contribute to disaster management, no general solutions will be possible, although we have given some guidance as to what type of data control will be applicable in which situation. Also, other aspects of VGI for disaster management need to be considered further. In particular, research is needed to illuminate the volunteers' motivation in contributing data to understand possible bias, but also to understand how people can be motivated to join. Also, methods need to be developed for expoiting the vast amount of unstructured information made available over the Internet after disasters and for integrating this information into the disaster management process.

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