Volunteered Geographic Information for people-centred severe weather early warning: A literature review

Sara Harrison[1],
Sally Potter[2],
Raj Prasanna[1],
Emma E. H. Doyle[1],
David Johnston[1]

[1] Joint Centre for Disaster Research, Massey University, New Zealand.

[2] GNS Science, New Zealand.

Author correspondence:
Sara Harrison,
Joint Centre for Disaster Research,
Private Box 756,
Wellington 6140
New Zealand.
Email: S.Harrison@massey.ac.nz

URL: http://trauma.massey.ac.nz/issues/2020-1/AJDTS_24_1_Harrison.pdf

Abstract

Early warning systems (EWSs) can prevent loss of life and reduce the impacts of hazards. Yet, recent severe weather events indicate that many EWSs continue to fail at adequately communicating the risk of the hazard, resulting in significant life and property loss. Given these shortcomings, there has been a shift towards people-centred EWSs to engage with audiences of warnings to understand their needs and capabilities. One example of engaging with warning audiences is through the collection and co-creation of volunteered geographic information (VGI). Much of the research in the past has primarily focused on using VGI in disaster response, with less exploration of the role of VGI for EWSs.

This review uses a scoping methodology to identify and analyse 29 research papers on EWSs for severe weather hazards. Results show that VGI is useful in all components of an EWS, but some platforms are more useful for specific components than are others. Furthermore, the different types of VGI have implications for supporting people-centred EWSs. Future research should explore the characteristics of the VGI produced for these EWS components and determine how VGI can support a new EWS model for which the World Meteorological Organization is advocating: that of impact-based forecasting and warning systems.

Keywords: *early warning system, people-centred early warning system, volunteered geographic information, disaster risk reduction, severe weather*

Early warning systems (EWSs) can prevent loss of life and reduce the impacts of hazards by providing members of the stakeholders and the public with information about likely, imminent risks on which they can act to prepare themselves and their property. As such, they have been a focus of disaster risk reduction since the Hyogo Framework for Action 2005-2015 through to the current Sendai Framework for Disaster Risk Reduction 2015-2030 (UNISDR, 2005, 2015). EWSs are described as having four key operational components: Disaster Risk Knowledge; Detection, Monitoring, and Warning Services; Communication and Dissemination Mechanisms; and Preparedness and Response Capacity (see Figure 1; Basher, 2006; Golnaraghi, 2012).

The first component, Disaster Risk Knowledge, involves systematically collecting and analysing data related to risk, such as the exposure and vulnerability of people and infrastructure to nearby hazards (Ahmed et al., 2012; Basher, 2006; Sai, Cumiskey, Weerts, & Bhattacharya, 2018). This involves assessing risk and vulnerability, building evacuation plans, and tailoring warning systems. Detection, Monitoring, and Warning Services make up the second component and are central to EWSs. This component requires reliable technology and involves continuous, automated detection and hazard monitoring (Ahmed et al., 2012; Basher, 2006; Sai et al., 2018). Furthermore, data, forecasts, and warnings should be archived for post-event analysis and

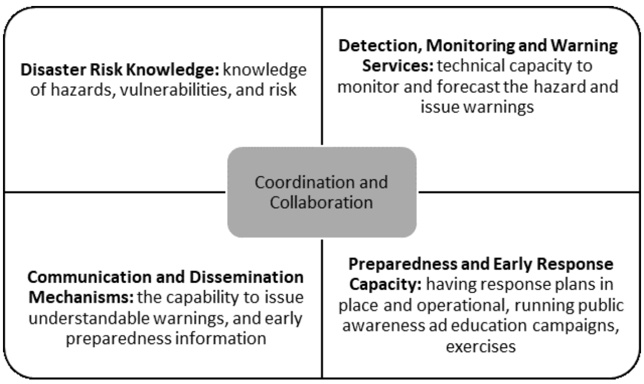

Figure 1. Four operational components of an early warning system. Adapted from Basher (2006), Golnaraghi (2012), and WMO (2018).

for continual system improvements (Ahmed et al., 2012; Basher, 2006; Sai et al., 2018). Impact data collected during and after a severe weather event would support both of these first two components (Harrison, Silver, & Doberstein, 2015).

The third component of an EWS is Communication and Dissemination, which is needed to reach those at risk. This involves using clear, concise, and understandable messages to enable proper preparedness (Ahmed et al., 2012; Basher, 2006; Sai et al., 2018). Multiple communications channels are necessary to reach as many people as possible (Ahmed et al., 2012; Basher, 2006). The fourth component of an EWS is Preparedness and Early Response Capacity. This involves running education and preparedness programmes to help people "understand their risks, respect the national warning services, and know how to react to warning messages" (WMO, 2018, p. 6). All four components of an EWS play a key role in crisis and risk communication.

EWSs share common characteristics with crisis and emergency risk communication theory. Like EWSs, the goal of crisis and risk communication theory is to provide sufficient and appropriate information to stakeholders that would allow them to "make the best possible decisions about their well-being" in a short period of time under uncertainty (Reynolds & Quinn, 2008, p. 14S). This involves understanding stakeholder (including the public) perceptions of risk and of the effectiveness of response, understanding the needs, capabilities, experiences, and predispositions of the stakeholders, and formulating messages based on these understandings for different audiences throughout the stages of crisis (Morgan, Fischhoff, Bostrom, Lave, & Atman, 1992; Reynolds & Seeger, 2005; Veil, Reynolds, Sellnow, & Seeger, 2008). Crisis and emergency risk communication theory is applied in risk messaging, crisis messaging, and warnings for health and emergency situations including, but not limited to, disease outbreaks, bioterrorism, hurricanes, and tornadoes (Reynolds & Seeger, 2005). The EWS framework presented in Figure 1 is thus supported by objectives of crisis and emergency risk communication theory, although the EWS framework does not include an apparent consideration for two-way communication: a key component in crisis and emergency risk communication theory for evaluating the effectiveness of communication (Garcia & Fearnley, 2012; Veil et al., 2008).

Recent severe weather events indicate that many EWSs continue to fail at adequately communicating the risk (and associated impacts) of the hazard, resulting in significant life and property loss due to limited understanding of, and response to, warnings (Ching, Carr de los Reyes, Sucaldito, & Tayag, 2015; Fleming et al., 2015; Wagenmaker et al., 2011). As such, there has been a push for "people-centred" EWSs to bring the "human factor" into consideration when designing and implementing EWSs and issuing warnings.

People-Centred Early Warning Systems

The broader EWS literature has recognised a communication gap between warning services and warning recipients, resulting in target audiences taking inadequate protective action despite receiving warnings (Anderson-Berry et al., 2018; Basher, 2006; Weyrich, Scolobig, Bresch, & Patt, 2018). In 2006, Basher introduced the concept of people-centred EWSs to address the "human factor" in EWSs, as he stated "failures in Early Warning Systems typically occur in the communication and preparedness elements" (Basher, 2006, p. 2168). Since then, there has been a shift towards people-centred EWSs which are developed for, and with, the target audiences to identify their needs and capacities and to transfer responsibility back to the audience to take protective actions (Basher, 2006; Scolobig, Prior, Schröter, Jörin, & Patt, 2015).

The United Nations Office for Disaster Risk Reduction (UNDRR; formerly known as the UNISDR) listed "investing in, developing, maintaining and strengthening people-centred multi-hazard, multi-sectoral forecasting, and Early Warning Systems" as an objective towards meeting the fourth priority of the Sendai Framework (UNISDR, 2015, p. 21). This "people-centred" aspect involves incorporating local and indigenous knowledge about hazards, promoting and applying low-cost EWSs that are appropriate to the audience based on their needs and capabilities, and broadening information channels (UNISDR, 2015; WMO, 2018). According to the Sendai Framework, people-centred EWSs can be developed through engagement with the audiences of warnings (e.g., individuals, communities, sectors: UNISDR, 2015; WMO, 2018).

One such example of engaging with warning audiences and understanding their needs and capabilities is through volunteered geographic information (VGI; WMO, 2017). VGI is information produced by or gathered from the public with associated locational attributes. The location-based information from VGI allows officials to identify high-risk areas, populations, and infrastructure

(Goodchild & Glennon, 2010; Granell & Ostermann, 2016; Haworth, 2018; Roche, Propeck-Zimmermann, & Mericskay, 2011).

Volunteered Geographic Information

VGI is valuable to disaster management because disasters are inherently location- and time-dependent and the location information from VGI allows officials to understand where the high-risk areas and populations are (Goodchild, 2007; Goodchild & Glennon, 2010; Granell & Ostermann, 2016; Haworth, 2018; Roche et al., 2011). The broader literature body around VGI, crowdsourcing, citizen science, and social media discusses and debates the relationship of these terms to each other and their associated characteristics and differences. It is argued that VGI overlaps both with citizen science and crowdsourcing (Cooper, Coetzee, & Kourie, 2018; Haklay, 2013, 2017). In Haklay's (2013) typology, crowdsourcing is classified as the lowest level of participation in citizen science. Citizen science (including crowdsourcing) is considered VGI when the information produced through the differing levels of participation includes geographic information (Haklay, 2017).

VGI can be collected in various ways, producing different types and formats of data. From reviewing the VGI and disaster risk reduction literature, we identified four types of VGI that are generally produced and/or collected for disaster risk reduction; these are summarised in Table 1. Geo-located social media refers to VGI that is posted online by social media users that has associated geographical location information. The term social media recognises online blogs, micro-blogs, online social networking, and forums, which enable sharing of text, audio, photographs, and videos (Alexander, 2014). Facebook, Twitter, Sina Weibo, WeChat, Instagram, and SnapChat are some examples of popular social media platforms. During a severe weather event, authorities can use social media to disseminate alerts and warnings and collect information from members of the public about the event and its impacts (Alexander, 2014; de Albuquerque et al., 2017; Goodchild, 2007; Harrison & Johnson, 2016; Roche et al., 2011; Simon, Goldberg, & Adini, 2015; Slavkovikj, Verstockt, Van Hoecke, & Van de Walle, 2014).

For this review, crowdsourcing refers to gathering information from active public participation, namely reports submitted via online forms or mobile applications (Harrison & Johnson, 2016). Crowdsourcing has historically been used in the response to a disaster for building situational awareness, coordinating resources, and aiding response efforts (Harrison & Johnson, 2016; Haworth & Bruce, 2015; Poblet, Garcia-Cuesta, Casanovas, 2014). Within the severe weather context,

Table 1
Summary of Volunteered Geographic Information types.

VGI Process	Spatial Data Format	Data Type	Data Sources	Disaster Risk Reduction Phase	Analysis/Outcomes
Geo-located social media harvesting	Point data	Impact data, exposure data, vulnerability data, hazard data Photos, videos, text	Facebook, Instagram, Twitter, Snapchat, Flickr, Sina Weibo, etc.	All	Cluster analysis, early detection, situational awareness, post-event damage/ impact assessment, response coordination
Crowdsourcing	Point data	Impact data, exposure data, vulnerability data, hazard data Photos, videos, text	Online reporting forms, mobile application	Readiness, Risk Reduction, During, Response	Cluster analysis, early detection, situational awareness, damage/impact assessment, response coordination
Participatory mapping/ Participatory GIS	Point, line, polygon	Impact data, exposure data, vulnerability data, hazard data, expert local knowledge Shapefiles	Community members, community leaders, stakeholders	Readiness, Risk Reduction, Recovery	Hazard and risk assessments/modelling, impact forecasting, customise/personalise warnings systems for the community, identify impact thresholds, inform/improve readiness and reduction efforts based on local knowledge
Local Knowledge	Point, line, polygon, written, audio	Impact data, exposure data, vulnerability data, hazard data, expert local knowledge Shapefiles	Community members, community leaders, stakeholders, experts	Readiness, Risk Reduction, Recovery	Hazard and risk assessments/modelling, impact forecasting, customise/personalise warnings systems for the community, identify impact thresholds, inform/improve readiness and reduction efforts based on local knowledge

crowdsourcing was used in the aftermath of Hurricane Katrina to locate missing people and allocate response efforts (Roche et al., 2011). In other examples, crowdsourcing is used for people on the ground to submit reports on flood levels and weather phenomena observations (Harrison & Johnson, 2016; Horita et al., 2018).

Participatory mapping and participatory Geographic Information Systems (participatory GIS) use local spatial knowledge to create spatial data or to verify and update existing data (Peters-Guarin, Mccall, & van Westen, 2012). Participatory mapping generally evolves into participatory GIS when hand-drawn maps or features are digitised and integrated into a GIS for further analysis (Brown & Kyttä, 2014; Forrester & Cinderby, 2011). Participatory mapping is often used to map exposure and vulnerability to hazards in communities to support disaster risk planning (Gaillard & Pangilinan, 2010; Haklay, Antoniou, & Basiouka, 2014). For weather-related hazards, Haworth, Whittaker, and Bruce (2016) found that participatory mapping enabled local knowledge exchange for community preparedness to bushfire risks.

Local knowledge refers to knowledge possessed by locals about their communities, neighbourhoods, traditions, history, environment, and hazards, among others. Local knowledge has not been clearly defined in the literature. For the purposes of this paper, we consider local knowledge as information gathered in similar participatory mapping and participatory GIS processes but not translated into a map or GIS. Recently, the access to and integration of local knowledge has been recognised for its importance to disaster risk reduction (Anderson-Berry et al., 2018; Gall & Cutter, 2016; Sebastian et al., 2017; UNISDR, 2015).

Past research has focused heavily on the role of VGI in disaster response, with less exploration in understanding how VGI can inform warnings before or during a severe weather event (Harrison & Johnson, 2016; Haworth & Bruce, 2015; Horita, Degrossi, Assis, Zipf, & de Albuquerque, 2013; Klonner et al., 2016). In Klonner and colleagues' (2016) systematic literature review, the authors focused on documenting research on VGI for preparedness and mitigation but did not provide clear findings in the context of warnings for severe weather. Assumpção, Popescu, Jonoski, and Solomatine (2018) identified the role of citizen observations in providing data for flood modelling and forecasting to solve issues of data scarcity, but again with no mention of warnings.

The original conception of VGI began with identifying its value for early detection and warning of hazards, using "citizens as sensors" (Goodchild, 2007). Since then, some work has emerged exploring VGI for early warnings of various hazards, such as earthquakes, landslides, and tsunami (Carley, Malik, Landwehr, Pfeffer, & Kowalchuck, 2016; Elwood, Goodchild, & Sui, 2012; Goodchild, 2007; Granell & Ostermann, 2016; Harrison & Johnson, 2016). Horita, de Albuquerque, Marchezini, and Mendiondo (2016) argued that VGI may help address challenges of assigning proper warning thresholds by incorporating local knowledge of response capabilities. Meissen and Fuchs-Kittowski (2014) developed a conceptual framework which demonstrated how crowdsourced data can be fully integrated into an existing EWS as another dataset to augment or enhance the warnings by providing context. However, no further evidence to date indicates the adoption into practice of this framework for any type of EWS. Finally, Marchezini and colleagues (2018) conducted a literature review of research on citizen science and EWSs and found that more research is needed to identify how citizen science can be "mainstreamed" into EWSs.

Some agencies have started collecting VGI to detect, monitor, and track events and their impacts. In the United Kingdom (UK), the British Geological Survey collects landslide impact data from Twitter including text descriptions, photos, and video footage of the resulting impacts (Pennington, Freeborough, Dashwood, Dijkstra, & Lawrie, 2015). These data are integrated into the National Landslide Database, which is used to create a Hazard Impact Model (Pennington et al., 2015). In Canada, the National Meteorological Service uses hazard information posted by the public on Twitter to detect weather events such as tornadoes and to verify and update current weather watches and warnings (Harrison & Johnson, 2016). However, there is a gap in the literature for fully characterising the role of VGI for severe weather warnings. It is important to fill this gap because information and knowledge possessed by citizens have the potential to uncover "areas of importance or concern" that have yet to be identified in an official capacity (Haworth, Bruce, & Middleton, 2012, p. 40). VGI offers a way to capture local knowledge about previous severe weather events and their extent, severity, and resulting impacts, as well as information on the local exposure and vulnerability that warning services may not necessarily possess (Fleming et al., 2015; GFDRR, 2016; Krennert, Pistotnik, Kaltenberger, & Csekits, 2018; Sai et al., 2018; WMO, 2017). This paper uses a scoping review method to identify previous research into the use of VGI for severe weather EWSs, to attempt to answer the research question: *What are the current and potential uses of VGI for severe weather warnings?* The objective of this review is to determine how VGI has been, or could be, used within EWSs for severe weather hazards.

Method

This literature review uses a scoping method to explore areas of existing research and identify research gaps in VGI for severe weather early warning systems (Arksey & O'Malley, 2005; Paré, Trudel, Jaana, & Kitsiou, 2015). Scoping reviews provide a "rigorous and transparent method for mapping areas of research" in a short time (Arksey & O'Malley, 2005, p. 30). The aim is to describe the nature of the current literature on VGI for severe weather EWSs by describing the quality and quantity of the research (Grant & Booth, 2009; Paré et al., 2015). Scoping reviews are recognised for their strength in providing a broad picture of the state of research in a given topic area and are well-cited in the information systems field (Grant & Booth, 2009; Paré et al., 2015; Tan et al., 2017). This scoping review follows the five-step process defined by Arksey and O'Malley (2005): 1) identify the research question, 2) identify relevant studies, 3) select studies, 4) chart the data, and 5) report the results.

Table 2
Search string employed in EBSCO Discovery and Scopus databases.

Topics covered	Search string statement
Warnings and Disaster Risk Knowledge	("risk communication" OR "warning*" OR "impact model*" OR "risk model*" OR "impact warning*" OR "impact*based warning*" OR "impact forecast*" OR "impact*based forecast*" OR "risk*based warning*" OR "risk*based communication")
	AND
A broad definition of VGI to include social media, participatory mapping, local knowledge based on location	("participatory" OR "participatory mapping" OR "VGI" OR "volunteered geographic information" OR "participatory GIS" OR "PGIS" OR "geographic crowdsourc*" OR "citizen science" OR "crowdsourc*" OR "social media")
	AND
Severe weather hazards as defined under the WWRP HIWeather Implementation Plan (Jones & Golding, 2014)	("weather" OR "storm*" OR "snow*" OR "wind*" OR "tornado*" OR "hurricane*" OR "cyclone*" OR "typhoon*" OR "monsoon*" OR "flood*" OR "mudslide" OR "flash flood*" OR "rain*" OR "wildfire")

The initial literature search involved developing a search string to capture the broad topic area of VGI and social media for warning of severe weather hazards. The search string comprised three joined statements, shown in Table 2, to cover warnings and Disaster Risk Knowledge (as per the first component of the EWS framework: Basher, 2006; Golnaraghi, 2012), VGI, and severe weather, which were entered into two academic-focused databases, Scopus and EBSCO Discovery Service, in August 2018. Literature review papers have been published on similar topics in this space that have searched no more than two databases (e.g., Klonner et al., 2016; Tan et al., 2017). Furthermore, Scopus is recognised for indexing a larger number of journals than other databases and is the largest searchable citation and abstract source for various scientific fields (Falagas, Pitsouni, Malietzis, & Pappas, 2008; Guz & Rushchitsky, 2009). Moreover, when searching the two databases many duplicate results were found between the two databases, ensuring confidence in the coverage.

"Participatory GIS" and "participatory mapping" are different types of VGI, and thus were identified as separate search terms. During the process of developing the search string, it was found that additional VGI research was left out of the search due to the specificity of "participatory mapping" and "participatory GIS", thus the search was widened with the term "participatory" to capture more VGI studies. Similarly, "flash flood" and "flood" are likely redundant, however, they were both included to ensure full coverage. The asterisk in the search string acts as a *wildcard* to search for variations of the root term. The search covered all years from the earliest available until mid-2018 and included only peer-reviewed journals and conference proceedings in English. The search resulted in 1,015 hits from Scopus and 122 from EBSCO. After removing duplicates, 1,027 unique publications were captured.

The following inclusion-exclusion criteria were used to select publications most relevant to this study:

1) Publications that specifically focused on severe weather hazards as defined under the World Weather Research Programme's (WWRP) High Impact Weather Implementation Plan (Jones & Golding, 2014; n = 254);
2) Studies that explicitly discussed warnings, preparedness, mitigation, impact modeling and

forecasting, or risk mapping (reducing to *n* = 141); and,

3) Studies that focused on VGI, crowdsourcing, citizen science, participatory mapping, local knowledge gathering, or social media data (reducing to *n* = 42).
4) Finally, publications had to be original, complete research papers (*n* = 29).

After applying the inclusion-exlcusion criteria, information from the resulting papers was extracted according to different categories (see Table 3). Initially, the severe weather hazard(s) considered in the study were identified, after which the EWS framework was used to classify the papers and determine how VGI is or could be used within the EWS framework (these results are presented later in Figure 3). This classification involved identifying for which EWS component the VGI was used (see Figure 1), followed by the element within the EWS component (i.e., the specific task, tool, or process that the VGI was used for within the EWS component, such as risk mapping, detection, monitoring, forecasting, or warning dissemination). The VGI platform was identified (e.g., participatory mapping, participatory GIS, social media, crowdsourcing, citizen science, local knowledge), as well as the type of data that was collected (Haklay, 2017; Harrison & Johnson, 2016). These categories were chosen to determine the representation of VGI in severe weather EWSs.

Results

The search of the two databases led to 1,027 unique publications. After applying the inclusion-exclusion criteria, the final number of papers selected for this study was 29. The categories listed in Table 3 were used as a structure for analysis and discussion, and were chosen based upon the dominance of those themes in the papers.

Table 3
Categories for literature review.

Category	Description
Hazard	The type of severe weather hazard(s) considered in the study.
Early Warning System Component	The component from the EWS framework that each study applies to.
VGI Platform	The source of the VGI data, such as from social media, or from crowdsourcing (i.e., citizen observation), citizen science (i.e., a higher level of engagement than crowdsourcing; Haklay, 2013), participatory mapping, participatory GIS, or local knowledge.
Data Type	The type of data that was collected through the VGI process, such as local knowledge captured through interviews and/or participatory mapping, hazard data from social media or crowdsourcing, etc.

Hazard Type

The selected articles covered a range of severe weather hazards as defined in the World Weather Research Programme (WWRP) High Impact Weather (HIWeather) implementation plan (Jones & Golding, 2014). Some hazards are represented more than others; of the 29 articles, 16 focused on flood hazards, followed by seven studies that covered general severe weather hazards, two studies that examined rain-induced landslides, two for cyclones, and one each for air quality and urban heat wave.

The 16 flood studies covered a range of elements within the EWS components. These elements were identified by reviewing the selected studies and aligning them with the EWS components. Table 4 provides a summary of the selected studies which examined floods. Most studies covered flood detection, monitoring, and forecasting using VGI collected from social media and crowdsourcing. The next most common elements that were covered in the flood studies were vulnerability

Table 4
Summary of selected studies covering flood hazards.

EWS Component	Element	Purpose of the study	VGI Platform	Data Type	Reference
Disaster Risk Knowledge	Modelling	To integrate local knowledge into GIS outputs for flood risk management using participatory GIS in order to understand how people cope and adapt	Participatory GIS	Interviews with households in Barangay, Philippines	Peters-Guarin et al., 2012
	Modelling	Validating flood models using quantitative and qualitative VGI	Participatory Mapping	Local knowledge from workshop participants and interviewees	Rollason et al., 2018
	Risk mapping	To provide an example of how to engage and collaborate with local stakeholders for flood management	Participatory Mapping	Land feature layers, input from locals	Lavers et al., 2018

Table 4 *(continued)*

	Vulnerability assessment	To present a risk management framework that is based on local knowledge of the vulnerability to water hazards	Local knowledge	Meetings, workshops, interviews with people, media, and public sectors related to risk management	Arias et al., 2016
	Vulnerability assessment	To present a new methodology for incorporating stakeholder's participation, local knowledge, and locally spatial characteristics for vulnerability assessments of flood risk	Participatory GIS	Demographic data, infrastructure, hazard data (e.g., average annual rainfall), questionnaire interviews with experts and community members	Hung & Chen, 2013
	Vulnerability assessment	To present a new database for collection and assessment of flood damage using a bottom-up approach to gather and identify damage data	Social media	Personal blogs, on-site observations, public administration, social media, online media, local authorities, corporate websites	Saint-Martin et al., 2018
Detection, Monitoring, Warning Services	Detection	To develop a service-oriented architecture for flood management to capture real-time information about floods	Crowdsourcing	Rainfall, river, news, OpenStreetMap	Sharma et al., 2016
	Detection	To develop a methodology for interpreting image tags on social media for early detection of a flood and recording the impacts	Social media	Flickr posts - timestamps and location metadata	Tkachenko et al., 2017
	Detection, Forecasting	SWOT analysis of web-based access to data and model simulations, and insight on pEWMS, and conceptual framework for a Nordic pEWMS	Crowdsourcing, Social Media	Denmark: groundwater level observations Iceland: flood photos Finland: mobile phone observations	Henriksen et al., 2018
	Detection, Monitoring	To assess social media feasibility for flood detection, monitoring, and forecasting and develop a novel methodology for doing so	Social media	Twitter data	Rossi et al., 2018
	Forecasting	To develop a methodology using social media for estimating rainfall runoff estimations and flood forecasting	Social media	Twitter data	Restrepo-Estrada et al., 2018
	Forecasting	To present a real-time modelling framework to identify likely flooded areas using social media	Social Media	Twitter data, LiDAR	Smith et al., 2017
	Monitoring	To estimate flood severity in an urban coastal setting using crowdsourced data	Crowdsourcing	Crowdsourced street flooding reports	Sadler et al., 2018
	Monitoring	To present a conceptual framework for collecting and integrating heterogeneous data from sensor networks and VGI	Crowdsourcing	Flood data from in-situ sensors and volunteers	Horita et al., 2015
	Monitoring	To present a new methodology for monitoring flood hazards using remote sensing and VGI	Crowdsourcing, Social Media	Volunteered data (photos, videos, news), Landsat, DEM, meteorological data, river data	Schnebele & Cervone, 2013
Detection, Monitoring, Warning Services; Communication and Dissemination Mechanism; Preparedness and Early Response Capacity	Warning messaging, preparedness	To test if evidence exists for social media reducing flood losses by informing mitigation decisions before the flood	Social media	Surveys, in-depth interviews with households who experienced flooding in Bangkok, 2011	Allaire, 2016

assessments and risk mapping and modelling, using VGI from participatory GIS, participatory mapping, local knowledge, and social media. Just one study looked at using social media for detection, warning messaging, and for informing preparedness decisions (Allaire, 2016).

The remaining 13 studies covered other hazards, such as general severe weather, cyclones, landslides, air quality, and urban heatwaves. Table 5 provides a summary of the selected studies covering these various hazards. The general category refers to studies that did not identify a specific severe weather hazard, but referred only to "severe weather", usually in the context of severe weather warnings (Fdez-Arroyabe, Lecha Estela, & Schimt, 2018; Grasso & Crisci, 2016; Grasso, Crisci, Morabito, Nesi, Pantaleo, et al., 2017; He, Ju, Xu, Li, & Zhao, 2018; Krennert et al., 2018; Longmore et al., 2015; Lu et al., 2018).

In the general category, most of the selected studies looked at detection and forecasting using social media and crowdsourcing, followed by tracking warning dissemination across social media, and one study that used crowdsourcing for both risk and vulnerability assessment and providing warnings. The two cyclone studies each used social media and local knowledge to detect and forecast cyclone damage and to understand local responses to warnings, respectively. The two landslide studies both used VGI for landslide hazard and impact modelling, using crowdsourcing and social media. Finally, both the air quality and urban heatwave studies explored VGI from social media to forecast air quality and detect heatwaves based on individual exposure.

These studies indicate that VGI is used in the mapping, modelling, detection, monitoring, and warning of a number of severe weather hazards but that floods are the most heavily studied, with the widest range of VGI application across all of the elements. How these studies fit within the EWS framework is analysed in the following section.

Early Warning System Components

The papers were categorised by EWS component, as per Basher's (2006) framework (see Figure 1): 1) Disaster Risk Knowledge (n = 8); 2) Detection, Monitoring, and Warning Services (n = 16); 3) Communication and Dissemination Mechanisms (n = 2); and 4) Preparedness and Early Response Capacity (n =1). Two studies were found to fall into more than one EWS component. The studies were then classified by the specific elements within each component (e.g., hazard mapping, risk mapping, vulnerability assessment, modelling, hazard monitoring, detection, monitoring, warning, messaging, dissemination).

Disaster Risk Knowledge. Eight studies fall into the Disaster Risk Knowledge component of the EWS framework. Four of these studies looked at the use of VGI for hazard, risk, or impact modelling for landslides and floods (Choi, Cui, & Zhou, 2018; Pennington et al., 2015; Peters-Guarin et al., 2012; Rollason, Bracken, Hardy, & Large, 2018). Choi and colleagues (2018) presented a crowdsourcing-based smartphone application to aggregate landslide reports, which populates a landslide database for further hazard analysis. Similarly, Pennington and colleagues (2015) presented a landslide database for the UK that is partially populated by reports from Twitter to capture their impacts for further modelling. In the floods space, Peters-Guarin and colleagues (2012) utilised participatory GIS to integrate local knowledge of coping and adaptation practices into GIS-based flood risk analysis. Alternatively, Rollason and colleagues (2018) used participatory mapping to validate existing flood models.

The other four studies in the Disaster Risk Knowledge component involved risk mapping and vulnerability assessments, also for floods (Arias et al., 2016; Hung & Chen, 2013; Lavers & Charlesworth, 2018; Saint-Martin et al., 2018). Lavers and Charlesworth (2018) engaged with landowners to capture their knowledge of flood risk to inform flood management. Arias and colleagues (2016) presented a risk management framework for floods based on local knowledge of the vulnerability to water hazards. Hung and Chen (2013) incorporated stakeholders' participation and local knowledge through participatory GIS for vulnerability assessments of flood risk. Saint-Martin and colleagues (2018) developed a flood damage database (DamaGIS) to collect and assess flood damage, sourced from corporate websites, personal blogs, local authorities, on-site observations, social media, and online media. Furthermore, Saint-Martin and colleagues argued that social media can extend coverage to areas lacking regular media coverage and reveal damage that might have otherwise gone undetected.

Detection, Monitoring, and Warning. Within the Detection, Monitoring, and Warning component, 16 studies were identified. Four studies used VGI for hazard detection. Tkachenko, Jarvis, and Procter (2017) and Sharma and colleagues (2016) looked at VGI for

Table 5
Summary of selected studies covering other severe weather hazards.

Hazard	EWS Component	Element	Purpose of the study	VGI Platform	Data Type	Reference
General	Disaster Risk Knowledge; Detection, Monitoring, Warning Services	Risk mapping	To present a data infrastructure that can be used to delineate individual vulnerability to meteorological changes	Crowdsourcing	User profiles on a mobile app	Fdez-Arroyable et al., 2018
	Detection, Monitoring, Warning Services	Detection	To present an Android-based application for geohazard reduction using crowdsourcing	Crowdsourcing	Crowdsourced information (field data, photos, videos)	He et al., 2018
		Detection, Monitoring	To present a conceptual framework for collecting weather photos	Crowdsourcing	User reports, photos, videos	Longmore et al., 2015
		Detection, Monitoring	To evaluate the occurrence of crowdsourcing for severe weather within European NMHSs	Crowdsourcing, Social Media	Surveys with European National Meteorological and Hydrological Services	Krennert et al., 2018
		Forecasting	To use social media as a new way of forecasting and generating traffic alerts due to weather hazards	Social media	Temporal, spatial, traffic, and meteorological data from Weibo	Lu et al., 2018
	Communication and Dissemination Mechanism	Warning dissemination	To study the use of codified hashtags relating to weather warnings in Italy	Social media	Twitter data	Grasso & Crisci, 2016
		Warning dissemination	To evaluate the use of a list of predefined codified hashtags for weather warnings in Italy	Social media	Twitter data	Grasso et al., 2017
Cyclone	Detection, Monitoring, Warning Services	Forecasting	To determine if social media and geo-location information can contribute to a more efficient early warning system and help with disaster assessment	Social media	Twitter data, Hurricane damage loss data	Wu & Cui, 2018
	Preparedness and Early Response Capacity	Response to warnings	To integrate local and scientific meteorological knowledge and actions within coconut farming communities in the Philippines	Local knowledge	Interviews with key stakeholders	Ton et al., 2017
Landslide	Disaster Risk Knowledge	Modelling	To present a crowdsourcing smartphone app for landslide reports which populates a landslide database	Crowdsourcing	Crowdsourced landslide reports from app users	Choi et al., 2018
		Modelling	To present a national landslide database in the UK which is partially populated with social media data to capture the impacts of landslides and for early detection of landslides	Social media	Twitter data	Pennington et al., 2015
Air quality	Detection, Monitoring, Warning Services	Forecasting	To explore the use of social media as a real-time data source for forecasting smog-related health hazards	Social media	Social media data and physical sensors data	Chen et al., 2017
Urban heat wave	Detection, Monitoring, Warning Services	Detection	To investigate the relationship between heat exposure and tweet volume over time	Social media	Twitter data	Jung & Uejio, 2017

detecting floods and capturing impacts from social media and crowdsourced data respectively. Jung and Uejio (2017) tested the effectiveness of measuring heat exposure on social media and consequently detecting urban heatwaves. Similarly, He and colleagues (2018) developed a crowdsourcing application to detect various weather hazards and to capture impacts to improve the decision-making of local governments. Henriksen and colleagues (2018) indicated the role of social media and crowdsourcing for both detection and forecasting of floods, while Rossi and colleagues (2018) assessed the feasibility of social media for flood detection and monitoring. Longmore and colleagues (2015) presented a conceptual crowdsourcing framework for collecting photos of severe weather hazards in the United States to improve weather monitoring by the National Weather Service. In Europe, Krennert and colleagues (2018) assessed the occurrence of crowdsourcing (either through specialised applications or social media) by national hydrological and meteorological services to capture severe weather observations and impacts for real-time warning verification and improvement.

VGI for forecasting alone was used for floods, cyclone damage, general severe weather traffic impacts, and air quality. Restrepo-Estrada and colleagues (2018) developed a methodology using social media for estimating rainfall runoff estimations and flood forecasting, while Smith, Liang, James, Lin, and Qiuhua Liang (2017) presented a real-time modelling framework to identify likely flooded areas using social media. Alternatively, Wu and Cui (2018) found that geo-located social media can help with disaster assessment, and for future forecasting. Lu and colleagues (2018) explored how social media might be used to forecast and generate traffic alerts due to severe weather. Likewise, Chen, Chen, Wu, Hu, and Pan (2017) explored social media for real-time forecasting of smog-related hazards.

Finally, three studies used VGI to monitor floods. Schnebele and Cervone (2013) crowdsourced from social media and other online media to monitor flood hazards and to create hazard maps, finding that the VGI is useful when satellite data is unavailable. Horita, de Albuquerque, Degrossi, Mendiondo, and Ueyama (2015) developed a framework to integrate crowdsourced flood observations with official sensor data. The authors found that the VGI made it possible to capture data from areas lacking flood sensors (Horita et al., 2015). Sadler, Goodall, Morsy, and Spencer (2018) crowdsourced street flooding reports to estimate flood severity for flood prediction, but the poor temporal and spatial coverage of the crowdsourced reports hindered the performance of the prediction model (Sadler et al., 2018).

Communication and Dissemination Mechanisms. Two studies were identified for the third EWS component, Communication and Dissemination Mechanisms. Both studies used VGI to assess warning dissemination via social media (namely Twitter) for general severe weather (Grasso & Crisci, 2016; Grasso, Crisci, Morabito, Nesi, Pantaleo, et al., 2017). Grasso and Crisci (2016) analysed codified hashtags of regions in Italy impacted by rainfall and found that codified hashtags for different regions effectively enable the sharing of useful information during severe weather events. Additionally, many tweets included geo-location information along with hazard information to update and complement official data. As such, the authors argued that institutions might adopt codified hashtags to improve the performance of systems for disseminating and retrieving information. Grasso and colleagues (2017) built on this work by adding more regions to their tweet analyses and emphasised the importance of institutions and warning services to promote codified hashtags for warnings to streamline message delivery and reach.

Preparedness and Early Response Capacity. For the last component, Preparedness and Early Response Capacity, only one study applied. Ton, Gaillard, Cadag, and Naing (2017) collected VGI in the form of local knowledge using interviews and questionnaires with farmers to understand their response to cyclone warnings. In this process, the farmers identified economic, physical, social, and natural impacts of cyclone hazards. The authors found that while farmers forecast weather conditions and impacts based on their local knowledge, their confidence in the lead-time of their forecasts has declined due to changing climate conditions. As such, the authors argued for the integration of local knowledge with scientific forecasts to verify local knowledge-based forecasts and increase confidence.

Multiple components. Two studies were found to fall into more than one EWS component. Allaire (2016) used VGI for Detecting, Monitoring, and Warning, assessing Communication and Dissemination Mechanisms, and for measuring Preparedness and Early Response capacities for flood hazards. Allaire (2016) found that social media was an effective tool for flood monitoring (falling in the Detection, Monitoring, and Warning component), for receiving and spreading flood information (as a Communication and Dissemination Mechanism), and for receiving and spreading preparedness information, leading to reduced impacts (informing Preparedness and Early Response Capacity). Alternatively, Fdez-Arroyable and colleagues (2018) developed a mobile application to obtain individual vulnerabilities to meteorological changes (thus informing Disaster Risk Knowledge) and to provide personalised alerts based on the individual vulnerabilities to meteorological conditions (informing Detection, Monitoring, and Warning services).

VGI Platforms and Data Types

In this review, we broadly define VGI to include participatory mapping, participatory GIS, geo-located social media, and location-based local knowledge (de Albuquerque, Eckle, Herfort, & Zipf, 2016). Figure 2 shows the distribution of platforms discussed in each of the selected studies and to which component of the EWS framework they apply. The following section provides definitions of the platforms displayed in Figure 2 along with a description of how the VGI is used for severe weather warnings.

Geo-located social media. Geo-located social media refers to VGI that is posted online by users of Facebook, Twitter, Sina Weibo, Flickr, YouTube, Instagram, and SnapChat that has geographical location information associated to it. The heavy representation of social media (15 studies) demonstrates the growing popularity of these platforms as a data source for severe weather events (Tkachenko et al., 2017). The results indicate that social media is a valid tool for measuring the effectiveness of warning dissemination by following Twitter hashtags (Allaire, 2016; Grasso & Crisci, 2016; Grasso, Crisci, Morabito, Nesi, Pantaleo, et al., 2017; Taylor, Kox, & Johnston, 2018). The online platforms are also useful for early hazard detection and for estimating

	Disaster Risk Knowledge	Detection, Monitoring, Warning Services	Communication and Dissemination Mechanism	Preparedness and Early Response Capacity	Total
Geo-located Social Media	2	9	3	1	15
Crowdsourcing	2	6			8
Crowdsourcing and Geo-located Social Media		3			3
Local Knowledge	1			1	2
Participatory Mapping/PGIS	4				4
Total	9	18	3	2	32

Figure 2. Distibution of VGI platforms used for each early warning system (EWS) framework component. Two studies fell into multiple components and have been counted for each EWS component that they apply to, which results in a total of 32, rather than 29.

event magnitude for early warnings (Chen et al., 2017; Jung & Uejio, 2017; Restrepo-Estrada et al., 2018; Tkachenko et al., 2017). Reasons for collecting social media data were to increase coverage of the dataset(s), the ease of access and quantity of data available, real-time or near-real-time monitoring and collection, and the multi-directional communication during disaster enabled by social media (Allaire, 2016; Chen et al., 2017; Grasso & Crisci, 2016; Grasso, Crisci, Morabito, Nesi, & Pantaleo, 2017; Jung & Uejio, 2017; Pennington et al., 2015; Rossi et al., 2018; Saint-Martin et al., 2018; Smith et al., 2017; Wu & Cui, 2018).

Crowdsourcing applications and forms. Eight of the selected studies used crowdsourcing via mobile applications, reporting forms, or other active contributions (e.g., storm spotters). The crowdsourcing applications in the selected studies were used for hazard detection and monitoring and for developing personalised risk knowledge. These applications allow citizens to report the occurrence of hazards such as landslides (Choi et al., 2018; He et al., 2018) and to monitor hazards such as rainfall-induced floods (Horita et al., 2015) and storms (Krennert et al., 2018; Longmore et al., 2015). The ability to efficiently collect reports and monitor hazards in real-time, in a standardised format to ensure quality, and to increase the scale and resolution of hazard-related data were arguments made for using crowdsourcing as opposed to other VGI collection types (Choi et al., 2018; He et al., 2018; Henriksen et al., 2018; Horita et al., 2015; Longmore et al., 2015; Sadler et al., 2018; Sharma et al., 2016).

Participatory mapping and participatory GIS. In the selected studies, participatory mapping and participatory GIS were employed for severe weather risk assessments and hazard modelling. Lavers and Charlesworth (2018) engaged UK farmers in participatory mapping to identify flood impacts on their properties and subsequent opportunities for mitigation. Peters-Guarin et al. (2012) had locals in the Philippines map their historical knowledge of recurring floods and impacts for a risk assessment. In Taiwan, Hung and Chen (2013) consulted with locals and stakeholders to verify flood vulnerability maps. Participatory mapping and interviews were utilised by Rollason and colleagues (2018) to validate flood models using local knowledge and experiences. In all of these studies, the mapped information was entered into a GIS for further mapping and analysis, thus qualifying it as participatory GIS. Reasons for using participatory GIS and participatory mapping over other types of VGI were formally recognising and integrating local knowledge in a systematic way, and supporting local engagement (Hung & Chen, 2013; Lavers & Charlesworth, 2018; Peters-Guarin et al., 2012; Rollason et al., 2018).

Local knowledge. For the purposes of this paper, we consider local knowledge as information gathered in participatory processes containing knowledge of the participants' local area and geography, that may or may not be translated onto a map. Just one selected study included local knowledge. After evaluating local knowledge of cyclone hazards and response capabilities to scientific knowledge, Ton and colleagues (2017) argued that local knowledge should be integrated with scientific meteorological knowledge for verification and to increase confidence in forecasts. The choice of using local knowledge for this study was to begin a dialogue between the locals and the meteorologists towards building trust (Ton et al., 2017).

Discussion

The results show that VGI is useful in all components of the early warning system (EWS) framework, but some platforms are more useful for specific components than are others. Furthermore, the different types of VGI have implications for supporting people-centred EWSs, which is a guiding principle for EWSs under the Sendai Framework.

Volunteered Geographic Information in Severe Weather Early Warning Systems

The purpose of this study is to determine the current and potential uses of VGI for severe weather warnings. We used the EWS framework to guide the analysis of the results.

The results from this literature review show that VGI has value in all four components of an EWS for severe weather hazards (Basher, 2006), but some forms of VGI are more useful for specific EWS components than are others (see Figure 3). Figure 3 is an update of Figure 1 based on the findings from this literature review to better represent how the different types of VGI inform or support the EWS components. For example, the majority of included studies used social media and crowdsourcing for hazard detection, monitoring, and early warning, while all of the included participatory mapping and participatory GIS studies used VGI for building disaster risk knowledge.

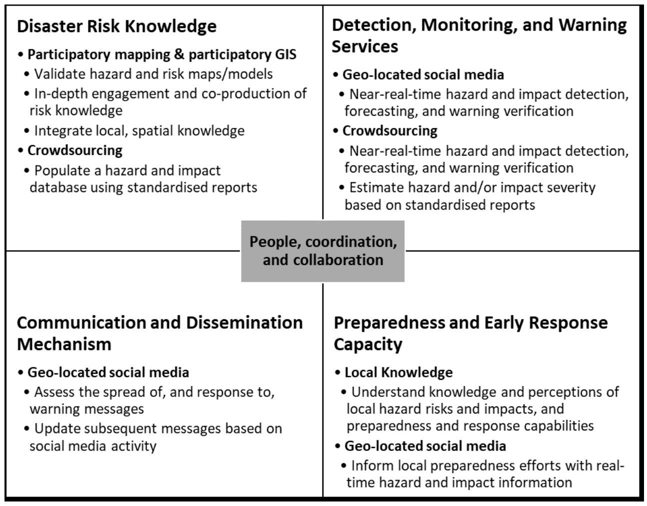

Figure 3. Volunteered Geographic Information for people-centred severe weather early warning systems.

The selected studies show that social media and crowdsourcing for severe weather are effective for early detection, monitoring, and verifying warnings (e.g., Harrison & Johnson, 2016; Henriksen et al., 2018; Krennert et al., 2018). The value of social media and crowdsourcing for EWSs lies in the real-time, or near-real-time, hazard and impact detection, forecasting, and warning verification (Henriksen et al., 2018; Kox, Kempf, Lüder, Hagedorn, & Gerhold, 2018; Krennert et al., 2018). However, the papers included in this scoping review lack forward-thinking for integrating these tools into official EWSs which is a challenge for warning services and emergency management services (Haworth, 2016; Henriksen et al., 2018; Kox et al., 2018). Despite this challenge, some national hydrological and meteorological services and emergency management agencies in Europe and North America collect information from social media for detection, monitoring, and warning verification (Harrison & Johnson, 2016; Henriksen et al., 2018; Krennert et al., 2018; Pennington et al., 2015).

Social media supports multi-directional communication, which allows for both crowdsourcing and broadcasting severe weather information. While most of the selected social media studies demonstrated the value of social media for detection and early warning, two studies also indicated its utility for disseminating warnings and assessing the spread of, and response to, warning messages (Grasso & Crisci, 2016; Grasso, Crisci, Morabito, Nesi, Pantaleo, et al., 2017). This allows warning services to gauge the reach of their message, understand the responses to their message, and update subsequent messages based on what they see on social media (Harrison & Johnson, 2016).

Before warnings are issued, knowledge of disaster risk is needed to be able to create tailored warnings. Participatory mapping and participatory GIS might be considered a long-term process for building knowledge and datasets for improving disaster risk knowledge as well as validating hazard and risk maps or models. While social media is valuable for real-time detection and communication, the participatory nature of participatory mapping enables more in-depth engagement with locals and communities in other areas of the EWS process to produce new knowledge (Haworth, 2018; Lavers & Charlesworth, 2018; Maskrey, Mount, Thorne, & Dryden, 2016; Peters-Guarin et al., 2012; Zolkafli, Brown, & Liu, 2017). Integrating local, spatial knowledge about disaster risk into an EWS through participatory mapping and participatory GIS fosters efforts towards people-centred EWSs as it translates local knowledge into usable and useful spatial data for risk analysis and for improved warnings (Basher, 2006; UNISDR, 2015).

These results support the findings from Marchezini and colleagues (2018), who presented a framework for bridging citizen science into EWSs. Like Marchezini and colleagues (2018), we found that VGI processes can bridge the gap between EWSs and audiences of warnings by incorporating local knowledge and personal experiences from stakeholders into the EWS components (see also Ton et al., 2017). This creates new data and unearths vulnerabilities at various scales (e.g., from the individual level to the community level; Haworth, 2018; Henriksen et al., 2018; Kox et al., 2018; Ton et al., 2017).

Implications for the different types of VGI. The results show that social media is a dominant platform for collecting VGI across severe weather hazards. Given the ease of access to, and the versatility of, social media (Harrison & Johnson, 2016), it is not surprising that social media is the most common platform used across hazards for collecting VGI (Granell & Ostermann, 2016). Social media is also now considered a "go-to" for collecting data because it is where the members of the public already are, thus groups or agencies looking to crowdsource do not have to do the heavy-lifting of creating a new app and attracting new users (Harrison & Johnson, 2016).

The perceived benefits of social media also come with some caveats. The data tend to be biased due to the uneven distribution of the social media user base (Granell & Ostermann, 2016; Harrison & Johnson, 2019). By relying on social media as a data source, those members of the public who are not present on social media are not represented in the data nor in the EWS process (i.e., the digital divide; Allaire, 2016; Harrison & Johnson, 2019). Additionally, tweet or post ambiguity and keyword selection for data-capture hinder data collection and analysis (Chen et al., 2017; Longmore et al., 2015; Tkachenko et al., 2017). Assimilating data of different formats into a database remains a challenge (Horita et al., 2015; Lu et al., 2018).

Capturing enough geo-located social media data is a constant challenge. It is widely known that only a small percentage of tweets contain geo-located information (Steed et al., 2019). Furthermore, the accessibility and availability of geo-located social media data are continuously limited. For example, Facebook does not offer an Application Programming Interface (API) to allow for researchers or media agencies to systematically collect Facebook posts, much less geo-located posts; it only offers an API for marketing and advertising agencies (Dubois, Zagheni, Garimella, & Weber, 2018; Thakur et al., 2018). In addition, in June 2019 Twitter announced plans to disable the geo-location feature for tweets due to its limited adoption by users and growing privacy concerns; however, the feature will still be available on photos taken within the Twitter mobile application (Benton, 2019; Khalid, 2019). While geo-located information on Instagram appears to be available for the moment (Arapostathis, 2019; Boulton, Shotton, & Williams, 2016), given the recent trends in the other major social media platforms, the continued availability and accessibility of this data in the future is uncertain.

A specialised crowdsourcing application can help to address some limitations found in social media. Crowdsourcing applications offer quality assurance, noise avoidance, application customisation, and citizen engagement (Choi et al., 2018; Longmore et al., 2015). On the other hand, crowdsourcing applications remain limited in the volume of participation due to public motivation to participate, the digital divide, and privacy concerns (Choi et al., 2018; Fdez-Arroyabe et al., 2018). Bias in reporting is also a concern, as contributors may over-exaggerate their personal experiences (Fdez-Arroyabe et al., 2018). Developing an application has the potential to streamline the integration of crowdsourced data into official processes, yet maintenance costs impede the willingness of officials to do so (Choi et al., 2018).

Capturing and representing local knowledge through participatory mapping and participatory GIS may help in bridging the digital divide, ensuring data quality, and enabling data integration. Participatory mapping and participatory GIS also enable community engagement (Haworth et al., 2016; Lavers & Charlesworth, 2018; Peters-Guarin et al., 2012). Participatory mapping and participatory GIS can be done using paper-mapping, as was done by Rollason and colleagues (2018), Lavers and colleagues (2018), and Peters-Guarin and colleagues (2012), or through digital-mapping (Haworth et al., 2016). In addition to the value of the resulting information and data itself, the process of engaging with and between locals provides another level of value in the social context by strengthening social networks, growing social capital, and increasing civic participation (Haworth et al., 2016).

Participatory GIS and participatory mapping do not come without their own limitations. For example, participatory GIS appears to be more effective with small-scale local projects. This is because most of the data collected is at a local or small scale, resulting in poor spatial distribution if scaled-up to a larger area. This could lead to underrepresentation and potential biases in the participatory GIS data (Rollason et al., 2018). Nevertheless, the rich quality and the ease of integrating this VGI into official processes may outweigh this limitation if the study is well-designed and the data is used appropriately (Brabham, 2013; Lauriault & Mooney, 2014). Within the EWS context, these perceived benefits further the movement towards people-centred EWSs by incorporating knowledge and information produced by the people into warnings that are ultimately for them (UNISDR, 2015).

Conclusion

This paper conducted a scoping literature review and explored 29 journal papers published in academic journals and conference proceedings retrieved from EBSCO Discovery and Scopus. The literature review found that VGI plays various roles for severe weather early warning systems (EWSs). The examples from the selected studies show that VGI furthers the development of people-centered EWSs; it brings people, their knowledge, and their experiences into EWSs. Still, the current research captured in this scoping review lacks forward-thinking for integrating these tools into official EWSs which is a challenge for warning services and emergency management services (Haworth, 2016; Henriksen et al., 2018; Kox et al., 2018).

In the always shifting EWSs landscape, a new type of severe weather EWS is emerging that is causing national meteorological and hydrological services and warning services to re-think their traditional warning practices. The World Meteorological Organization is advocating for the aforementioned services to adopt impact-based forecasts and warning systems (Fleming et al., 2015). Impact-based forecasts and warnings are meant to shift the focus from the physical hazard phenomena to the risk of impacts produced by the hazard, including communicating impacts in warning messages and building new warning thresholds based on risk of impact (Fleming et al., 2015; Morss, Cuite, Demuth, Hallman, & Shwom, 2018; Poolman, 2014; Potter et al., 2018; Robbins & Titley, 2018; Rogers, Kootval, & Tsirkunov, 2017; Sai et al., 2018). However, warning services have indicated a limited understanding of, and access to, the data required for developing impact-based forecasting and warning systems (Harrison et al., 2014; Kox et al., 2018; Obermeier & Anderson, 2014).

Future research would benefit from a systematic review of this topic area in the future. Additional research should investigate the data needs for impact-based forecasts and warnings and explore how VGI can help in meeting these data needs while also maintaining a people-centred focus. This would align with the goals of the World Meteorological Organization's High Impact Weather research programme (http://hiweather.net) which aims to improve the effectiveness of weather-related warnings in support of advances in weather prediction and forecasting (Zhang et al., 2019). While this literature review characterised the role of VGI within severe weather EWSs and demonstrated how it supports people-centred EWSs, future research can delve into the nature of the resulting data and how it might support impact-based forecast and warning systems. It should be noted that in spite of the popularity of collecting and using social media data, given the uncertainty of reliable access to social media data in the future (e.g., disestablishing the geolocation function on Twitter), it would be wise to minimise reliance on these platforms and consider additional VGI sources and collection processes to capture the desired information.

Acknowledgements

The authors thank the anonymous reviewers whose feedback greatly improved this manuscript. This research was supported by public research funding from the Government of New Zealand through GNS Science.

References

Alexander, D. E. (2014). Social media in disaster risk reduction and crisis management. *Science and Engineering Ethics, 20,* 717-733. doi: 10.1007/s11948-013-9502-z

Allaire, M. (2016). Disaster loss and social media: Can online information increase flood resilience? *Water Resources Research*, *52*, 7408–7423. doi: 10.1002/2014WR016618

Anderson-Berry, L., Achilles, T., Panchuk, S., Mackie, B., Canterford, S., Leck, A., & Bird, D. K. (2018). Sending a message: How significant events have influenced the warnings landscape in Australia. *International Journal of Disaster Risk Reduction*, *30*, 5–17. doi: 10.1016/j.ijdrr.2018.03.005

Arapostathis, S. G. (2019). Instagrammers report about the deadly wildfires of East Attica, 2018, Greece: An introductory analytic assessment for disaster management purposes. In *Proceedings of the 16th ISCRAM Conference* (pp. 473–481). València, Spain. Retrieved from https://github.com/h4t0n/

Arias, P. A., Villegas, J. C., Machado, J., Serna, A. M., Vidal, L. M., Vieira, C., … Mejía, Ó. A. (2016). Reducing social vulnerability to environmental change: Building trust through social collaboration on environmental monitoring. *Weather, Climate, and Society*, *8*(1), 57–66. doi: 10.1175/WCAS-D-15-0049.1

Arksey, H., & O'Malley, L. (2005). Scoping studies: Towards a methodological framework. *International Journal of Social Research Methodology*, *8*(1), 19–32. doi: 10.1080/1364557032000119616

Assumpção, T. H., Popescu, I., Jonoski, A., & Solomatine, D. P. (2018). Citizen observations contributing to flood modelling: Opportunities and challenges. *Hydrology and Earth System Sciences Discussions*, *22*, 1473–1489. doi: 10.5194/hess-2017-456

Basher, R. (2006). Global early warning systems for natural hazards: Systematic and people-centred. *Philosophical Transactions of the Royel Society*, *364*, 2167–2182. doi: 10.1098/rsta.2006.1819

Benton, J. (2019, June 19). Twitter is removing precise-location tagging on tweets — a small win for privacy but a small loss for journalists and researchers. *NiemanLab*. Retrieved from http://niemanlab.org

Boulton, C. A., Shotton, H., & Williams, H. T. P. (2016). Using social media to detect and locate wildfires. In *10th International AAAI Conference on Web and Social Media (ICWSM 16), W8: Social Web for Environmental and Ecological Monitoring*. Cologne, Germany. Retrieved from www.ushahidi.com/

Brabham, D. C. (2013). *Using crowdsourcing in government*. California, US: IBM Center for The Business of Government.

Brown, G., & Kyttä, M. (2014). Key issues and research priorities for public participation GIS (PPGIS): A synthesis based on empirical research. *Applied Geography*, *46*, 122–136. doi: 10.1016/j.apgeog.2013.11.004

Carley, K. M. K. M., Malik, M., Landwehr, P. M. P. M., Pfeffer, J., & Kowalchuck, M. (2016). Crowd sourcing disaster management: The complex nature of Twitter usage in Padang Indonesia. *Safety Science*, *90*, 48–61. doi: 10.1016/j.ssci.2016.04.002

Chen, J., Chen, H., Wu, Z., Hu, D., & Pan, J. Z. (2017). Forecasting smog-related health hazard based on social media and physical sensor. *Information Systems*, *64*, 281–291. doi: 10.1016/j.is.2016.03.011

Ching, P. K., Carr de los Reyes, V., Sucaldito, M. N., & Tayag, E. (2015). Responding to Typhoon Haiyan in the Philippines. *Western Pacific Surveillance and Response Journal*, *6*(Supplement 1), 1–4.

Choi, C. E., Cui, Y., & Zhou, G. G. D. (2018). Utilizing crowdsourcing to enhance the mitigation and management of landslides. *Landslides*, *15*, 1889-1899. doi: 10.1007/s10346-018-1034-9

Cooper, A. K., Coetzee, S., & Kourie, D. G. (2018). Volunteered geographical information, crowdsourcing, citizen science and neogeography are not the same. *Proceedings of the ICA*, *1*, 1–8. doi: 10.5194/ica-proc-1-131-2018

de Albuquerque, J. P., Eckle, M., Herfort, B., & Zipf, A. (2016). Crowdsourcing geographic information for disaster management and improving urban resilience: An overview of recent developments and lessons learned. In C. Capineri, M. Haklay, H. Huang, V. Antoniou, J. Kettunen, F. Ostermann, & R. Purves (Eds.), *European handbook of crowdsourced geographic information* (pp. 309–321). London: Ubiquity Press.

de Albuquerque, J. P., Horita, F. E. A., Degrossi, L. C., Rocha, R. dos S., Camargo de Andrade, S., Restrepo-Estrada, C., & Leyh, W. (2017). Leveraging Volunteered Geographic Information to improve disaster resilience. In A. Ballatore, B. Bennett, C. Claramount, C. J. Davis, S. Di Martino, A. Klippel, … B. Schoen-Phelan (Eds.), *Volunteered Geographic Information and the future of geospatial data* (pp. 158–184). Pennsylvania, US: IGI Global.

Dubois, A., Zagheni, E., Garimella, K., & Weber, I. (2018). Studying migrant assimilation through Facebook interests. In S. Staab, O. Koltsova, & D. Ignatov (Eds.), *Social informatics* (pp. 51–60). Switzerland: Springer, Cham.

Elwood, S., Goodchild, M. F., & Sui, D. Z. (2012). Researching Volunteered Geographic Information: Spatial data, geographic research, and new social practice. *Annals of the Association of American Geographers*, *102*(3), 571–590. doi: 10.1080/00045608.2011.595657

Falagas, M. E., Pitsouni, E. I., Malietzis, G. A., & Pappas, G. (2008). Comparison of PubMed, Scopus, Web of Science, and Google Scholar: Strengths and weaknesses. *The FASEB Journal*, *22*(2), 338–342. doi: 10.1096/fj.07-9492LSF

Fdez-Arroyabe, P., Lecha Estela, L., & Schimt, F. (2018). Digital divide, biometeorological data infrastructures and human vulnerability definition. *International Journal of Biometeorology*, *62*(5), 733–740. doi: 10.1007/s00484-017-1398-x

Fleming, G., Rogers, D., Davies, P., Jacks, E., Milton, J. A., Honore, C., … Goolaup, P. (2015). WMO Guidelines on Multi-Hazard Impact-Based Forecast and Warning Services [PDF file]. Retrieved from www.wmo.int/pages/prog/www/DPFS/Meetings/ET-OWFPS_Montreal2016/documents/WMOGuidelinesonMulti-hazardImpact-basedForecastandWarningServices.pdf

Forrester, J., & Cinderby, S. (2011). A guide to using community mapping and participatory-GIS [PDF file]. Retrieved from https://tweedforum.org/wp-content/uploads/2018/09/Borderlands-Community-Mapping-Guide.pdf

Gaillard, J. C., & Pangilinan, M. L. C. J. D. (2010). Participatory mapping for raising disaster risk awareness among the youth. *Journal of Contingencies and Crisis Management*, *18*(3), 175–179. doi: 10.1111/j.1468-5973.2010.00614.x

Gall, M., & Cutter, S. L. (2016). *Understanding disaster risk through loss data*. Washington, D.C.: International Bank for Reconstruction and Development/The World Bank. doi: 10.1016/0301-4207(78)90055-7

Garcia, C., & Fearnley, C. J. (2012). Evaluating critical links in early warning systems for natural hazards. *Environmental Hazards*, *11*(2), 123–137. doi: 10.1080/17477891.2011.609877

GFDRR. (2016). Implementing multi-hazard impact-based forecast and warning services [PDF file]. Retreived from www.gfdrr.org/sites/default/files/publication/Report%20on%20Implementing%20Multi%20Hazard%20Impact%20Based%20Forecast%20and%20Warning%20Services%2017-02-10%20Final.pdf

Golnaraghi, M. (Ed.). (2012). *Institutional partnerships in multi-hazard early warning systems*. Berlin: Springer.

Goodchild, M. F. (2007). Citizens as sensors: The world of Volunteered Geography. *GeoJournal*, *69*(4), 211–221.

Goodchild, M. F., & Glennon, J. A. (2010). Crowdsourcing geographic information for disaster response: A research frontier. *International Journal of Digital Earth*, *3*(3), 231–241. doi: 10.1080/17538941003759255

Granell, C., & Ostermann, F. O. (2016). Beyond data collection: Objectives and methods of research using VGI and geo-social media for disaster management. *Computers, Environment and Urban Systems*, *59*(2016), 231–243. doi: 10.1016/j.compenvurbsys.2016.01.006

Grant, M. J., & Booth, A. (2009). A typology of reviews: An analysis of 14 review types and associated methodologies. *Health Information and Libraries Journal*, *26*(2), 91–108. doi: 10.1111/j.1471-1842.2009.00848.x

Grasso, V., & Crisci, A. (2016). Codified hashtags for weather warning on Twitter: An Italian case study. *PLoS Currents Disasters*, *8*, 1–30. doi: 10.1371/currents.dis.967e71514ecb92402eca3bdc9b789529

Grasso, V., Crisci, A., Morabito, M., Nesi, P., & Pantaleo, G. (2017). Public crowdsensing of heat waves by social media data. *Advances in Science and Research*, *14*, 217–226. doi: 10.5194/asr-14-217-2017

Grasso, V., Crisci, A., Morabito, M., Nesi, P., Pantaleo, G., Zaza, I., & Gozzini, B. (2017). Italian codified hashtags for weather warning on Twitter - who is really using them? *Advances in Science and Research*, *14*, 63–69. doi: 10.5194/asr-14-63-2017

Guz, A. N., & Rushchitsky, J. J. (2009). Scopus: A system for the evaluation of scientific journals. *International Applied Mechanics*, *45*(4), 351–362. doi: 10.1007/s10778-009-0189-4

Haklay, M. (2013). Citizen science and Volunteered Geographic Information: Overview and typology of participation. In D. Sui, S. Elwood, & M. Goodchild (Eds.), *Crowdsourcing geographic knowledge: Volunteered Geographic Information (VGI) in theory and practice* (pp. 105–122). Dordrecht: Springer Netherlands.

Haklay, M. (2017). Volunteered Geographic Information and citizen science. Retrieved from www.opensignal.com/

Haklay, M., Antoniou, V., & Basiouka, S. (2014). Crowdsourced geographic information use in government. Retrieved from http://discovery.ucl.ac.uk/1433169/

Harrison, J., Mccoy, C., Bunting-Howarth, K., Sorensen, H., Williams, K., & Ellis, C. (2014). Evaluation of the National Weather Service Impact-based Warning tool [PDF file]. Retrieved from https://publications.aqua.wisc.edu/product/evaluation-of-the-national-weather-service-impact-based-warning-tool/

Harrison, S., & Johnson, P. A. (2016). Crowdsourcing the disaster management cycle. *International Journal of Information Systems for Crisis Response and Management*, *8*(4), 17–40. doi: 10.4018/IJISCRAM.2016100102

Harrison, S., & Johnson, P. A. (2019). Challenges in the adoption of crisis crowdsourcing and social media in Canadian emergency management. *Government Information Quarterly*, *36*, 501–509. doi: 10.1016/J.GIQ.2019.04.002

Harrison, S., Silver, A., & Doberstein, B. (2015). Post-storm damage surveys of tornado hazards in Canada: Implications for mitigation and policy. *International Journal of Disaster Risk Reduction*, *13*, 427–440. doi: 10.1016/j.ijdrr.2015.08.005

Haworth, B. (2016). Emergency management perspectives on volunteered geographic information: Opportunities, challenges and change. *Computers, Environment and Urban Systems*, *57*, 189–198. doi: 10.1016/j.compenvurbsys.2016.02.009

Haworth, B. (2018). Implications of Volunteered Geographic Information for disaster management and GIScience: A more complex world of volunteered geography. *Annals of the American Association of Geographers*, *108*(1), 226–240. doi: 10.1080/24694452.2017.1321979

Haworth, B., & Bruce, E. (2015). A review of Volunteered Geographic Information for disaster management. *Geography Compass*, *5*(9), 237–250. doi: 10.1111/gec3.12213

Haworth, B., Bruce, E., & Middleton, P. (2012). Emerging technologies for risk reduction: assessing the potential use of social media and VGI for increasing community engagement. *Australian Journal of Emergency Management*, *30*(3), 36–41.

Haworth, B., Whittaker, J., & Bruce, E. (2016). Assessing the application and value of participatory mapping for community bushfire preparation. *Applied Geography*, *76*, 115–127. doi: 10.1016/j.apgeog.2016.09.019

He, C., Ju, N., Xu, Q., Li, Y., & Zhao, J. (2018). Designing an Android-based application for geohazard reduction using citizen-based crowdsourcing data. *Mobile Information Systems*, *2018*, 1-11.

Henriksen, H. J., Roberts, M. J., van der Keur, P., Harjanne, A., Egilson, D., & Alfonso, L. (2018). Participatory early warning and monitoring systems: A Nordic framework for web-based flood risk management. *International Journal of Disaster Risk Reduction*, *31*, 1295–1306. doi: 10.1016/j.ijdrr.2018.01.038

Horita, F. E. A., de Albuquerque, J. P., Degrossi, L. C., Mendiondo, E. M., & Ueyama, J. (2015). Development of a spatial decision support system for flood risk management in Brazil that combines volunteered geographic information with wireless sensor networks.

Computers and Geosciences, *80*, 84–94. doi: 10.1016/j.cageo.2015.04.001

Horita, F. E. A., de Albuquerque, J. P., Marchezini, V., & Mendiondo, E. M. (2016). A qualitative analysis of the early warning decision-making process in disaster management. In *13th International Conference on Information Systems for Crisis Response and Management (ISCRAM 2016)*, (May 2016), 1–8.

Horita, F. E. A., Degrossi, L. C., Assis, L. F. ., Zipf, A., & de Albuquerque, J. P. (2013). The use of Volunteered Geographic Information and crowdsourcing in disaster management: A systematic literature review. In *Proceedings of the Nineteenth Americas Conference on Information Systems* (pp. 1–10).

Horita, F. E. A., Vilela, R. B., Martins, R. G., Bressiani, D. A., Palma, G., & de Albuquerque, J. P. (2018). Determining flooded areas using crowd sensing data and weather radar precipitation: A case study in Brazil. In *15th International Conference on Information Systems for Crisis Response and Management (ISCRAM 2018)* (May 2018), 1030–1039. Retrieved from www.scopus.com/inward/record.uri?eid=2-s2.0-85060678817&partnerID=40&md5=71160a6fc9ab22da45c84ad5116adbb9

Hung, H. C., & Chen, L. Y. (2013). Incorporating stakeholders' knowledge into assessing vulnerability to climatic hazards: Application to the river basin management in Taiwan. *Climatic Change*, *120*(1–2), 491–507. doi: 10.1007/s10584-013-0819-z

Jones, S., & Golding, B. (2014). HIWeather: A research activity on High Impact Weather within the World Weather Research Programme [PDF file]. Retrieved from www.wmo.int/pages/prog/arep/wwrp/new/documents/HIWeatherImplementationPlan.pdf

Jung, J., & Uejio, C. K. (2017). Social media responses to heat waves. *International Journal of Biometeorology*, *61*(7), 1247–1260. doi: 10.1007/s00484-016-1302-0

Khalid, A. (2019, June 19). Twitter removes precise geo-tagging option from tweets. *Engadget*. Retrieved from www.engadget.com

Klonner, C., Marx, S., Usón, T., Porto de Albuquerque, J., Höfle, B., Klonner, C., … Höfle, B. (2016). Volunteered Geographic Information in natural hazard analysis: A systematic literature review of current approaches with a focus on preparedness and mitigation. *ISPRS International Journal of Geo-Information*, *5*(7), 103. doi: 10.3390/ijgi5070103

Kox, T., Kempf, H., Lüder, C., Hagedorn, R., & Gerhold, L. (2018). Towards user-orientated weather warnings. *International Journal of Disaster Risk Reduction*, *30*, 74-80. doi: 10.1016/j.ijdrr.2018.02.033

Krennert, T., Pistotnik, G., Kaltenberger, R., & Csekits, C. (2018). Crowdsourcing of weather observations at national meteorological and hydrological services in Europe. *Advances in Science and Research*, *15*, 71–76. doi: 10.5194/asr-15-71-2018

Lauriault, T., & Mooney, P. (2014). Crowdsourcing: A geographic approach to public engagement. Retrieved from https://papers.ssrn.com/sol3/papers.cfm?abstract_id=2518233.

Lavers, T., & Charlesworth, S. (2018). Opportunity mapping of natural flood management measures: A case study from the headwaters of the Warwickshire-Avon. *Environmental Science and Pollution Research*, *25*(20), 19313–19322. doi: 10.1007/s11356-017-0418-z

Longmore, S., Miller, S., Bikos, D., Lindsey, D., Szoke, E., Molenar, D., … Knaff, J. (2015). An automated mobile phone photo relay and display concept applicable to operational severe weather monitoring. *Journal of Atmospheric and Oceanic Technology*, *32*(7), 1356–1363. doi: 10.1175/JTECH-D-14-00230.1

Lu, H., Zhu, Y., Shi, K., Lv, Y., Shi, P., & Niu, Z. (2018). Using adverse weather data in social media to assist with city-level traffic situation awareness and alerting. *Applied Sciences*, *8*(7), 1193-1210. doi: 10.3390/app8071193

Marchezini, V., Horita, F. E. A., Matsuo, P. M., Trajber, R., Trejo-Rangel, M. A., & Olivato, D. (2018). A review of studies on Participatory Early Warning Systems (P-EWS): Pathways to support citizen science initiatives. *Frontiers in Earth Science*, *6*, 1–18. doi: 10.3389/feart.2018.00184

Maskrey, S. A., Mount, N. J., Thorne, C. R., & Dryden, I. (2016). Participatory modelling for stakeholder involvement in the development of flood risk management intervention options. *Environmental Modelling and Software*, *82*, 275–294. doi: 10.1016/j.envsoft.2016.04.027

Meissen, U., & Fuchs-Kittowski, F. (2014). Crowdsourcing in early warning systems. In *Proceedings - 7th International Congress on Environmental Modelling and Software: Bold Visions for Environmental Modeling, iEMSs 2014* (pp. 326–332).

Morgan, G., Fischhoff, B., Bostrom, A., Lave, L., & Atman, C. J. (1992). Communicating risk to the public. *Environmental Science & Technology*, *26*(11), 2048–2056.

Morss, R. E., Cuite, C. L., Demuth, J. L., Hallman, W. K., & Shwom, R. L. (2018). Is storm surge scary? The influence of hazard, impact, and fear-based messages and individual differences on responses to hurricane risks in the U.S. *International Journal of Disaster Risk Reduction*, *30*, 44-58. doi: 10.1016/j.ijdrr.2018.01.023

Obermeier, H., & Anderson, M. R. (2014). Verification and analysis of impact-based tornado warnings in the central region of the National Weather Service. *Electronic Journal of Severe Storms Meteorology*, *10*(1), 1–20.

Paré, G., Trudel, M.-C., Jaana, M., & Kitsiou, S. (2015). Synthesizing information systems knowledge: A typology of literature reviews. *Information & Management*, *52*, 183–199. doi: 10.1016/j.im.2014.08.008

Pennington, C., Freeborough, K., Dashwood, C., Dijkstra, T., & Lawrie, K. (2015). The National Landslide Database of Great Britain: Acquisition, communication and the role of social media. *Geomorphology*, *249*, 44–51. doi: 10.1016/j.geomorph.2015.03.013

Peters-Guarin, G., Mccall, M. K., & van Westen, C. (2012). Coping strategies and risk manageability: Using participatory geographical information systems to represent local knowledge. *Disasters*, *36*(1), 1–27. doi: 10.1111/j.1467-7717.2011.01247.x

Poblet, M., Garcia-Cuesta, E., & Casanovas, P. (2014). Crowdsourcing tools for disaster management: A review of platforms and methods. In *AI approaches to the complexity of legal systems* (pp. 261–274). Germany: Springer.

Poolman, E. R. (2014). *A probabilistic impact-focussed early warning system for flash floods in support of disaster management in South Africa*. South Africa: University of Pretoria.

Potter, S. H., Kreft, P. V., Milojev, P., Noble, C., Montz, B., Dhellemmes, A., … Gauden-Ing, S. (2018). The influence of impact-based severe weather warnings on risk perceptions and intended protective actions. *International*

Journal of Disaster Risk Reduction, *30*, 34–43. doi: 10.1016/j.ijdrr.2018.03.031

Restrepo-Estrada, C., de Andrade, S. C., Abe, N., Fava, M. C., Mendiondo, E. M., & de Albuquerque, J. P. (2018). Geo-social media as a proxy for hydrometeorological data for streamflow estimation and to improve flood monitoring. *Computers and Geosciences*, *111*, 148–158. doi: 10.1016/j.cageo.2017.10.010

Reynolds, B., & Quinn, S. C. (2008). Effective communication during an influenza pandemic: The value of using a crisis and emergency risk communication framework. *Health Promotion Practice*, *9*(4), 13S-17S. doi: 10.1177/1524839908325267

Reynolds, B., & Seeger, M. W. (2005). Crisis and emergency risk communication as an integrative model. *Journal of Health Communication*, *10*(1), 43–55. doi: 10.1080/10810730590904571

Robbins, J. C., & Titley, H. A. (2018). Evaluating high-impact precipitation forecasts from the Met Office Global Hazard Map using a global impact database. *Meteorological Applications*, *25*(4), 548–560. doi: 10.1002/met.1720

Roche, S., Propeck-Zimmermann, E., & Mericskay, B. (2011). GeoWeb and crisis management: Issues and perspectives of volunteered geographic information. *GeoJournal*, *78*(1), 21–40. doi: 10.1007/s10708-011-9423-9

Rogers, D. P., Kootval, H., & Tsirkunov, V. V. (2017). Early warning, resilient infrastructure and risk transfer. In *Bridging science and policy implication for managing climate extremes* (pp. 65–79). Retrieved from www.gfdrr.org

Rollason, E., Bracken, L. J., Hardy, R. J., & Large, A. R. G. (2018). The importance of volunteered geographic information for the validation of flood inundation models. *Journal of Hydrology*, *562*, 267–280. doi: 10.1016/j.jhydrol.2018.05.002

Rossi, C., Acerbo, F. S., Ylinen, K., Juga, I., Nurmi, P., Bosca, A., … Alikadic, A. (2018). Early detection and information extraction for weather-induced floods using social media streams. *International Journal of Disaster Risk Reduction*, *30*, 145–157. doi: 10.1016/j.ijdrr.2018.03.002

Sadler, J. M., Goodall, J. L., Morsy, M. M., & Spencer, K. (2018). Modeling urban coastal flood severity from crowd-sourced flood reports using Poisson regression and Random Forest. *Journal of Hydrology*, *559*, 43–55. doi: 10.1016/j.jhydrol.2018.01.044

Sai, F., Cumiskey, L., Weerts, A., & Bhattacharya, B. (2018). Towards impact-based flood forecasting and warning in Bangladesh: A case study at the local level in Sirajganj district. Retrieved from www.nat-hazards-earth-syst-sci-discuss.net/nhess-2018-26/

Saint-Martin, C., Javelle, P., & Vinet, F. (2018). DamaGIS: A multisource geodatabase for collection of flood-related damage data. *Earth System Science Data*, *10*(2), 1019–1029. doi: 10.5194/essd-10-1019-2018

Schnebele, E., & Cervone, G. (2013). Improving remote sensing flood assessment using volunteered geographical data. *Natural Hazards and Earth System Science*, *13*(3), 669–677. doi: 10.5194/nhess-13-669-2013

Scolobig, A., Prior, T., Schröter, D., Jörin, J., & Patt, A. (2015). Towards people-centred approaches for effective disaster risk management: Balancing rhetoric with reality. *International Journal of Disaster Risk Reduction*, *12*, 202–212. doi: 10.1016/j.ijdrr.2015.01.006

Sebastian, A., Lendering, K., Kothius, B., Brand, N., Jonkman, S. N., van Gelder, P., … Lhermitte, S. (2017). *Hurricane Harvey Report: A fact-finding effort in the direct aftermath of Hurricane Harvey in the Greater Houston Region*. Delft: Delft University Publishers.

Sharma, V. K., Rao, G. S., Amminedu, E., Nagamani, P. V., Shukla, A., Rao, K. R. M., & Bhanumurthy, V. (2016). Event-driven flood management: design and computational modules. *Geo-Spatial Information Science*, *19*(1), 39–55. doi: 10.1080/10095020.2016.1151212

Simon, T., Goldberg, A., & Adini, B. (2015). Socializing in emergencies - A review of the use of social media in emergency situations. *International Journal of Information Management, 35*(5), 609-619. doi: 10.1016/j.ijinfomgt.2015.07.001

Slavkovikj, V., Verstockt, S., Van Hoecke, S., & Van de Walle, R. (2014). Review of wildfire detection using social media. *Fire Safety Journal*, *68*, 109–118. doi: 10.1016/J.FIRESAF.2014.05.021

Smith, L., Liang, Q., James, P., Lin, W., & Qiuhua Liang, C. (2017). Assessing the utility of social media as a data source for flood risk management using a real-time modelling framework. *Journal of Flood Risk Management*, *10*(3), 370–380. doi: 10.1111/jfr3.12154

Steed, R. J., Fuenzalida, A., Bossu, R., Bondár, I., Heinloo, A., Dupont, A., … Strollo, A. (2019). Crowdsourcing triggers rapid, reliable earthquake locations. *Science Advances*, *5*(4), 1-6. doi: 10.1126/sciadv.aau9824

Tan, M. L., Prasanna, R., Stock, K., Hudson-Doyle, E., Leonard, G., & Johnston, D. (2017). Mobile applications in crisis informatics literature: A systematic review. *International Journal of Disaster Risk Reduction*, *24*, 297–311. doi: 10.1016/j.ijdrr.2017.06.009

Taylor, A. L., Kox, T., & Johnston, D. (2018). Communicating high impact weather: Improving warnings and decision making processes. *International Journal of Disaster Risk Reduction*, *30*, 1–4. doi: 10.1016/j.ijdrr.2018.04.002

Thakur, G., Sims, K., Mao, H., Piburn, J., Sparks, K., Urban, M., … Bhaduri, B. (2018). Utilizing geo-located sensors and social media for studying population dynamics and land classification. In S.-L. Shaw & D. Sui (Eds.), *Human dynamics research in smart and connected communities* (pp. 13–40). Switzerland: Springer, Cham.

Tkachenko, N., Jarvis, S., & Procter, R. (2017). Predicting floods with Flickr tags. *PLoS ONE*, *12*(2), 1-13. doi: 10.1371/journal.pone.0172870

Ton, K. T., Gaillard, J. C., Cadag, J. R., & Naing, A. (2017). It takes two to tango: Integrating meteorological knowledge and actions for disaster risk reduction. *Climate and Development*, *9*(6), 479–492. doi: 10.1080/17565529.2016.1174658

UNISDR. (2005). Hyogo Framework for Action 2005-2015 [PDF file]. Retrieved from www.unisdr.org/files/1037_hyogoframeworkforactionenglish.pdf

UNISDR. (2015). Sendai Framework for Disaster Risk Reduction. doi: A/CONF.224/CRP.1

Veil, S., Reynolds, B., Sellnow, T. L., & Seeger, M. W. (2008). CERC as a theoretical framework for research and practice. *Health Promotion Practice*, *9*(4), 26-34. doi: 10.1177/1524839908322113

Wagenmaker, R., Weaver, J., Garnet, G., Perry, B., Spinner, J., & Mann, G. (2011). *NWS Central Region Service*

Assessment Joplin, Missouri, Tornado – May 22, 2011. Missouri, US: National Weather Service.

Weyrich, P., Scolobig, A., Bresch, D. N., & Patt, A. (2018). Effects of impact-based warnings and behavioural recommendations for extreme weather events. *Weather, Climate, and Society*, *10*, 781–796. doi: 10.1175/WCAS-D-18-0038.1

WMO. (2017). *Joint meeting of the Commission For Basic Systems Open Programme Area Group on Public Weather Services Delivery (Opag-Pwsd) Expert Teams on Impact of Multi- Hazard Prediction and Communication (Et/Impact) and on Services and Products Innovation and Improvement*. Switzerland: WMO.

WMO. (2018). *Multi-hazard early warning systems: A checklist*. Switzerland: WMO.

Wu, D., & Cui, Y. (2018). Disaster early warning and damage assessment analysis using social media data and geo-location information. *Decision Support Systems*, *111*, 48–59. doi: 10.1016/j.dss.2018.04.005

Zhang, Q., Li, L., Ebert, B., Golding, B., Johnston, D., Mills, B., … Keller, J. (2019). Increasing the value of weather-related warnings. *Science Bulletin*, *64*(10), 647–649. doi: 10.1016/j.scib.2019.04.003

Zolkafli, A., Brown, G., & Liu, Y. (2017). An evaluation of Participatory GIS (PGIS) for land use planning in Malaysia. *The Electronic Journal of Information Systems in Developing Countries, 83*, 1–23.